ENSURING ANIMAL HEALTH AND OTHER SERVICES FOR EFFICIENT AND INCLUSIVE LIVESTOCK VALUE CHAINS IN LMICS

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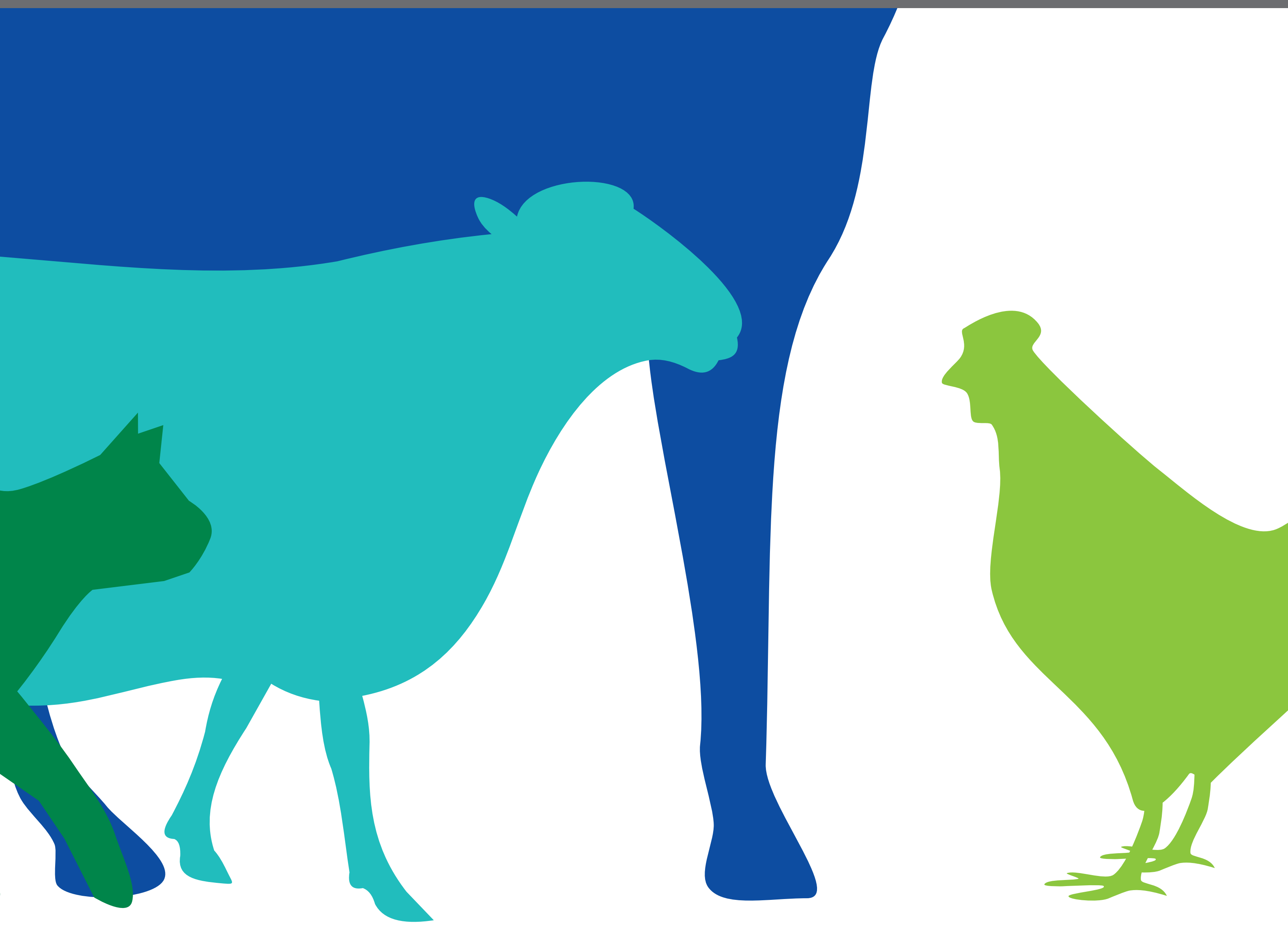

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ENSURING ANIMAL HEALTH AND OTHER SERVICES FOR EFFICIENT AND INCLUSIVE LIVESTOCK VALUE CHAINS IN LMICS

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EDITORIAL
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Editorial: Ensuring Animal Health and Other Services for Efficient and Inclusive Livestock Value Chains in LMICs

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Keywords: value chain, low and medium income countries, livelihoods, delivery system, livestock, animal health

Editorial on the Research Topic

Ensuring Animal Health and Other Services for Efficient and Inclusive Livestock Value Chains in LMICs

The livestock sector offers opportunity for many livestock producers in LMICs to improve their livelihoods (1). Under various scenarios (2), the demand for livestock-derived foods will continue to increase in these countries, offering market incentives to increase livestock production and productivity. However, livestock productivity remains very low. For example, annual milk yield of a cow in Sub-Saharan Africa and South Asia is 6 and 12%, respectively, of a cow in an OECD country. Within countries and production systems, yield gaps are high for all species (3). This suggests that productivity increase is feasible with changes in management, breeds, feeds and health practices, also considering ecological and social economic factors. One of the key constraints faced by livestock keepers is access to affordable and quality inputs and services—all needed to improve productivity. These include animal health inputs and services, feed and breeding, and also extension or advisory services. Different organizational arrangements for the delivery of such inputs and services have emerged, especially in the dairy and poultry sectors. Some of these arrangements are led by value chain actors themselves, while others have been promoted and supported by development agencies and donors. The effectiveness of these organizational arrangements remains insufficiently documented, limiting the opportunity to learn and apply lessons across value chains and countries. The objective of the research topic is to facilitate research and stimulate discussion regarding access to affordable and quality inputs and services that ultimately improve livestock production and productivity in a sustainable and equitable way.

The 12 papers included in this research topic cover a range of topics- nine papers focus on animal inputs and services (including seven on animal health, two on breeding/genetics and one on extension); one paper covers both health and genetics. In addition, two papers are about output markets and one on policies. Seven of the 12 papers are outputs of the CGIAR Research Program on Livestock that "aims to create a well-nourished, equitable, and environmentally healthy world through livestock research for development." The 12 submissions follow three general methodologies.

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The first set of papers falls into the "characterization studies" category. Three papers deal with the provision of animal health inputs and services. They highlight the inadequacy between livestock keepers' demand for these services, and the supply. Enahoro et al. presents a clear example of this phenomenon in the case of the poultry sector in Ghana and Tanzania. In addition, Gizaw et al. describes the co-existence of formal and informal systems in the provision of animal health services in Ethiopia and the dissatisfaction with the public sector in reaching particularly the pastoral community. Authors in this first set of papers also highlight the need for increased capacity development of service providers. This is exemplified with respect to food safety considerations in Dione et al. in the case of use of antimicrobial drugs in Uganda, and Murungi et al. in the case of pig traders and abattoirs in Nairobi, Kenya. The challenge of limited access and availability and low quality of inputs and services was also highlighted in the policy review of the dairy sector in Rwanda by Habiyaremye et al.

The second set of papers uses ex ante impact evaluation methodologies, to assess the likely effects of specific interventions in guiding policies and investments. One paper (Ouma et al.) focuses on farmers' demand for a vaccine against pig cysticercosis in Uganda; it concludes that as markets may not recognize this public health cost, pig producers will be willing to pay for vaccine only if they can pass on the costs to consumers. The authors call for public health interventions as private delivery of such a vaccine will likely not be successful. Also, to guide policies while focusing on output, Rich and Wane analyze the option for the cattle sector in Burkina Faso to shift from exporting beef (with the setup of abattoirs) in lieu of live animals to Ghana. Given the low competitiveness of the West African meat, compared to other imports, the authors urge that focus should rather be on increasing livestock productivity.

The third set of papers looks at the effects of new or improved livestock services, including their delivery on households' livelihoods. Dione et al. assesses the change in knowledge amongst pig producers in Uganda following the introduction of extension services using Interactive Voice Response (IVR) technology in delivering biosecurity messages for the control of African swine fever (ASF). Their study shows positive results in terms of improved knowledge, for those who had not had any training earlier but also to enhance knowledge for these who attended face to face trainings. Two other papers using this methodology analyze change in livestock productivity and income: Kassie et al. in the case of delivery of breeding and health services for small ruminants in Ethiopia and Teufel et al. for the case of the Infection and Treatment Method (ITM) against East Coast Fever in Tanzania. Kassie et al. using different specifications of difference-in-differences models show that access to small ruminant health services has increased a range of livestock productivity indicators (offtake, return per head, and gross income per adult equivalent). A similar conclusion was reached when comparing users of the ITM technology and the non-users (or rather these who adopted recently) in Tanzania. These two studies highlight the potential for livestock innovations to have positive and long-lasting effects on livelihoods.

It is also worth noting that a couple of studies highlighted gender differences. Among them, Gizaw et al. shows that women have lower access to animal health services in general in Ethiopia while Enahoro et al. makes the same observation for poultry farmers in Ghana and Tanzania. Extension services using mobile technology like IVR show less gender differences, as noted by Dione et al. in the case of pig farming in Uganda.

Overall, this Research Topic provides a good overview of the situation and challenges with respect to the delivery of livestock inputs and services, with a focus on Sub Saharan Africa. The papers discuss in particular the role of the public and private sectors, and the importance of unlicensed, informal, service providers. Interestingly no paper covered producer organizations as institutions supporting livestock producers' access to inputs and services, despite some evidence of their importance. It is also worth noting that many papers are characterization studies, with only three providing much-needed assessment of the effects of innovations, or new ways to provide inputs and services—on livestock productivity and resulting households' livelihoods. These three studies show that rigorous research design, while complex, is feasible, and the results are key in guiding further investments for the livestock sector in LMICs.

AUTHOR CONTRIBUTIONS

IB drafted the paper. SK and BB revised the manuscript. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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The Nairobi Pork Value Chain: Mapping and Assessment of Governance, Challenges, and Food Safety Issues

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The Nairobi pork food system is a growing livestock sub-sector which serves as a source of food and livelihood to its inhabitants. The study aimed to map Nairobi's pork value chains, assess their governance, operational challenges and their impacts on food safety risks and management practices. Qualitative data were collected in seven focus group discussions and 10 key informants' interviews on animal movements and product flows, stakeholders' interactions, perceptions on system governance and challenges, and on their potential impact on food safety management. Quantitative data were obtained to show the importance of flows, business operations and market share. Thematic analysis was conducted to identify themes that provide understanding on the governance, challenges and food safety practices in each profile. The predominant chains identified were [1] The "large integrated company" profile which accounted for 83.6% of pork marketed through abattoirs, and was based on a well-structured supply system, with owned farms (representing 50% of their supply), contract farms and semi-contract farms and [2] Local independent abattoirs, accounting for 16.4%, are privately owned small-scale production, supplied mainly (70%) by small farmers from the immediate neighboring areas. The main challenges associated with governance themes included; (i) Inadequate/lack of enforcement of existing regulation (ii) Negative effect of devolution system of governance (iii) Pig traders' dominance (iii) Lack of association at all system nodes, and (iv) Male dominance across the pig system. The main challenges reported included; (i) Lack of capital to upscale (ii) Poor infrastructure (iii) Pig shortage (iv) Excessive regulation (v) Lack of training (vi) Diseases (v) Lack of knowledge (vi) Unfair competition. Food safety themes were associated with (i) Inadequate slaughter facilities forcing traders/farmers to undertake home slaughter (ii) Lack of knowledge on disease management (iii) Lack of training on hygienic practices in the slaughterhouse and (iv) Lack/insufficient capital to purchase equipment's to ensure proper hygiene e.g., boilers. The study provides insights into the structure of the pork system supplying Nairobi, the governance issues important to the stakeholders, challenges and food safety issues. The framework obtained can be used by policy makers and researchers to investigate and develop pork industry and for food safety and disease control programmes.

Keywords: pork value chain, Nairobi, food system, mapping, governance, food safety, challenges

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INTRODUCTION

Recent estimates indicate that the demand for pork and poultry products in East Africa will increase 4-fold by 2030 (1). In Kenya, the increase in pork consumption is projected to increase 125 and 268% in 2030 and 2050, respectively (2). Much of this increase stems from changing consumption patterns attributed to urbanization, increasing incomes and human population growth. In this regard, the region mirrors change elsewhere in sub-Saharan Africa and more widely across similar low-income settings. Pork meat provides an opportunity to cater for the projected increasing demand for meat. There is an ongoing shift toward monogastric food systems, as pigs like other monogastric animals have shorter production cycles, require smaller land areas and have better concentrate feed conversion rates than ruminants (3). However, this diversification and increased demand has led to will lead to unintended consequences leading to food safety risks (4, 5). The risks range from increased environmental contamination to public health effects, because of an expected higher incidence of zoonotic pathogens and other infectious diseases. Therefore, with increased demand and expanding urbanization, food systems will need to adapt to meet consumer's demands, but at the same time to ensure safe quality products and avoid environmental problems. Understanding how the pork food system operates in a rapidly growing developing city is crucial to facilitate its adaptation and formulate recommendations on system improvements.

Nairobi is one of the rapidly growing cities in Africa with a population of 4.4 million people (6) and an estimated population of 305,489 pigs (7), equating to pig biomass of 0.11 kg per person (8). In Kenya the current per capita consumption of pork is 0.4 kg, behind bovine meat at 12.2 kg, mutton/goat at 2.2 kg, and poultry at 0.6 kg (8). Pork is one of the sectors with higher potential to grow and to provide increased economic opportunities for farmers (9, 10). Currently, intensive pig farming and free range scavenging systems are the most prevalent farming systems in the country (11, 12). The majority of peri-urban farmers in Nairobi confine their pigs (13, 14), while in rural areas, most pig keepers let their pigs scavenge for feed (15–18). This system is however common in urban Nairobi, in particular dumping sites (19), and is characterized by minimal or no health care, supplementary feeding, poor housing and high level of inbreeding (13, 15). In terms of pig abattoirs, few exist in Kenya and much of the slaughter takes place informally in farms and unlicensed slaughter points. The licensed abattoirs have clear market distinctions and functionality. There is one large pork processing firm in the country which accounts for over 80% of the national supply of processed products. Three other abattoirs (Ndumbuini, Lyntano, and Kabati), situated in Nairobi or its peri-urban area, represent the rest of the pork abattoirs serving the city. The remaining pork chains run through unorganized slaughter slabs and local backyard slaughtering (11).

There is a paucity of data on how the Nairobi pork system is organized and operated, with respect to market nodes, governance, challenges, and food safety issues. Such information is crucial to understand the sector, identify growth opportunities, and support national food safety policies and disease control programmes. For this, value chain analysis (VCA) studies are a useful approach to understanding the dynamics of the production system, flow of products and disease transmission impact on different actors' incentive structures and behaviors (20, 21), while facilitating understanding governance, upgrading opportunities, and structural deficiencies (14, 22). Governance represents the other key pillar of this analysis, and aims to understand the coordination and power distribution in the chains (22, 23). Assessing the governance of the system can then provide insight on how diseases are effectively managed in the chains by different stakeholders, especially in case of shocks, such as disease outbreaks. It can also help identify those stakeholders with the highest influence and capacity to dictate and enforce food safety norms or private standards. We have previously undertaken similar studies focused on other commodities (14, 24–26).

The aim of this study was, (i) to map the pork system supplying Nairobi through abattoirs, markets and urban, peri-urban pig keepers and retailers; and (b) to assess the challenges and governance of these chains and their potential influence on disease and food safety risk management.

MATERIALS AND METHODS

Study Site

We conducted a cross-sectional study throughout the pork food system in Nairobi city in 2013-2014. For this study, we visited the three major independent pig abattoirs supplying Nairobi: Ndumbuini abattoir in Kiambu county, Lyntano abattoir in Nairobi County and Kabati abattoir in Murang'a County. These abattoirs are named in this study as "Local independent abattoirs" (LIAs) as people in these systems are mostly independent workers and no one group of people or person controls a large process of operations. One large pork processing company was also visited in Nairobi, which integrates most parts part of rearing, sourcing of pigs, slaughter, and distribution of products. In this study it is named as "Integrated company" (IC). This company abattoir and the three LIAs represent the only formal slaughterhouses supplying pork to Nairobi. In addition, three areas of Nairobi were selected for the investigation of farmers and retailers. These were Kibera and Korogocho, two informal urban settlements, and Dagoretti, that could be considered as peri-urban Nairobi. City market, a meat wholesale market, was also visited.

Data Collection

Entry and Selection of Participants

For data collection in abattoirs and wholesale pork markets, a formal request was sent to the Ministry of Agriculture and Livestock to seek permission to conduct the study. The Director of Veterinary Services granted permission and gave an introduction to the District Veterinary Officers under whose jurisdiction the abattoirs lay. The District Veterinary Officers provided an authorization letter and introduced researchers to the corresponding chief meat inspectors in charge of abattoirs/markets. These in turn presented the research team to the market/abattoir owners. At each step, the project objectives and methods were explained and permission to conduct the

TABLE 1 | People interviewed for this study.

Abattoirs/ markets/ retailers	Type	No of participants
Ndumbuini abattoir	Pig traders (FGD)	17
	Pig brokers (FGD)	6
	Meat inspector (Interview)	1
Kabati abattoir	Pig traders (FGD)	5
	Abattoir manager and abattoir owner (Interviews)	2
	Meat inspector (Interview)	1
Lyntano abattoir	Abattoir manager (Interview)	1
	Meat inspector (Interview)	1
Integrated company	Managers involved of supply, sales, marketing manager, and quality assurance (Interviews)	3
Pig keepers	Small scale pig keepers in Dagoretti (peri-urban) (FGD)	16
	Small scale pig keepers in Kibera (informal settlements) (FGD)	13
Pork retailer	Public health officers (Dagoretti and Korogocho)- FGD	9
Pork wholesale market	Meat inspector	1

research was obtained. Through an initial discussion with the meat inspectors, abattoir owners or managers, the main types of people involved in the pork value chain associated with these abattoirs were identified. Subsequently, focus groups discussions (FGD) were conducted separately with each type of stakeholder and individual interviews were also organized. The meat inspector and abattoir owners facilitated selection of participants. These were asked to provide a range of different people of the same profession (e.g., ensure to have large- and small-scale pig traders) to maximize the identification and study of all different value chains. The presence of abattoir owners and meat inspectors during interviews and FGDs with other stakeholders was avoided, when possible, to avoid courtesy bias or influence responses.

For data collection from pig farmers, an introductory letter from the District Veterinary Officer was presented to the respective Livestock Production Officer in charge of the study area. The Livestock Production Officer is the operative with the most comprehensive knowledge of farmers and their practices. These were then requested to select pig farmers for FGDs and individual interviews in each of the areas. Two FGDs were organized, one in Kibera and one in Dagoretti to assess the differences between informal settlements and peri-urban areas. As with abattoirs, guidance was provided to recruit as much diversity of pig farming practices as possible e.g., small, medium and large-scale farmers; male and female. For the integrated company and city market, interviews with managers of these places were conducted. To assess information on retailers (such as butcheries), we interviewed the public health officers in charge of their inspections in two areas of Nairobi, Dagoretti (peri-urban area) and in Korogocho (an informal settlement). All the focus groups and interviews undertaken are summarized in **Table 1**.

Type of Data Collected

The study was conducted using a mixed method approach. Qualitative data collection was undertaken using interview guides to obtain information on value chain mapping, governance and disease and food safety management. Data collected on value chain mapping included: (i) the process of sourcing the pigs, through understanding the different type of sources animals are bought from, the main geographical areas and type of farms where the pigs came from and the choice rationale for selecting different points of origin; (ii) the methods of transportation of animals; (iii) the methods of slaughtering and carcass processing; (iv) the type of interaction between the different actors and products generated, (v) the distribution of products, including the geographical areas of destination; (vi) the types of farms that exist according to sizes and production methods; and (vii) the sources of inputs such as feeding, watering, and veterinary services. Quantitative data were collected from participants by asking them to estimate proportions of chain flows. When possible, these figures were obtained through consensus and /or by achieving a majority. Such information included output and volume of products distribution to various areas. For this all participants were given time to brainstorm on the different answers to come to a consensus. In addition, data from records from the certificate of transports available at one of the abattoirs visited for the period between November and December of 2014 were consulted. For each certificate data were collected on (i) the origin of the pigs moved, (ii) quantities of pigs moved, (iii) name of the trader, and (iv) movement date. Furthermore, data on abattoirs' activities, infrastructure and equipment were collected through researchers' observation using a checklist.

To collect data on value chain governance and challenges, participants were asked to (i) identify the different roles involved in the decision process and the actual performance of the activity; (ii) the type of relationships with other stakeholders in regards to transaction on animals, products and payments; (iii) their views on the power groups in the system and existing associations; (iv) their interaction with government officers and structures; and (v) to indicate gender dominance in their activities.

Data on disease control and food safety were collected by observation and completing a pre-prepared checklist. For this, the authors visited the premises of each abattoir during a normal working day. This information was triangulated by asking participants about possible safety challenges they encounter in their workplaces. We also asked farmers to state the main diseases affecting their farm, the source of animal health and production advice, the strategies employed to manage these diseases and the disposal methods for dead pigs.

The questions were carefully designed and implemented, to avoid leading answers and/or embarrassing participants. All focus groups and interviews were video and/or voice recorded to obtain all the information given by the respondents and minimize misinterpretation by researchers. Notes were also taken throughout all the discussions and interviews. The result

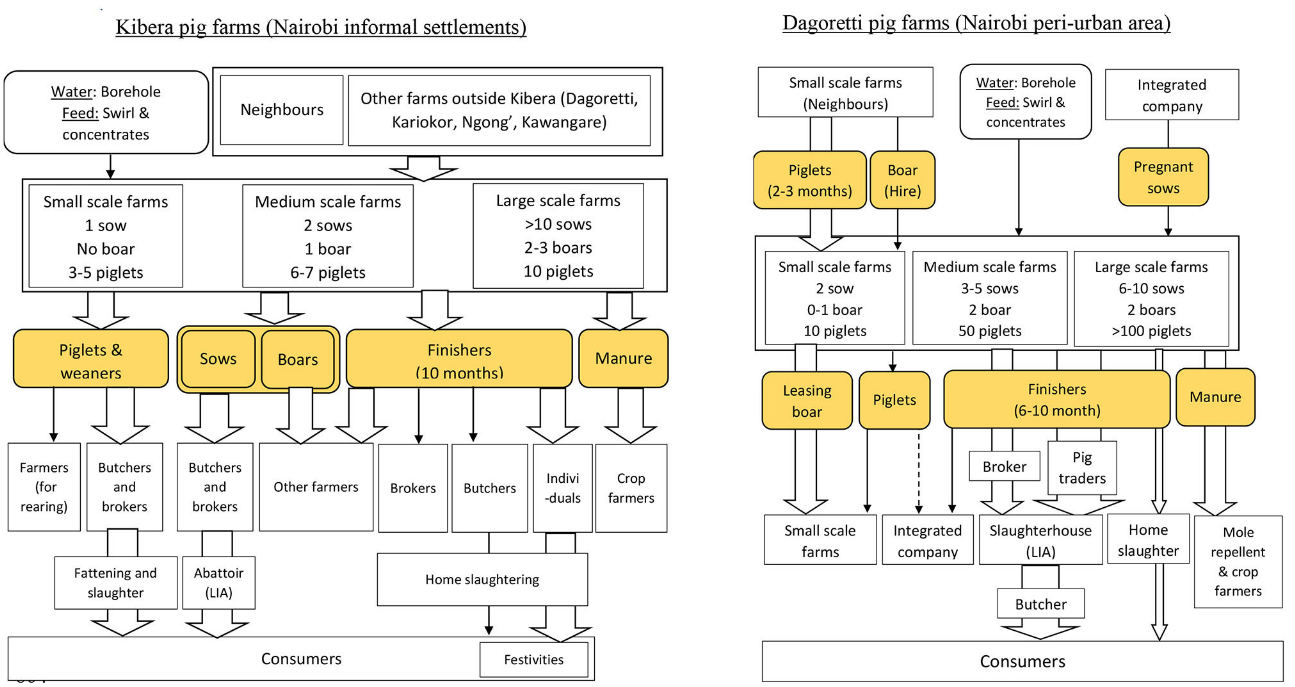

FIGURE 1 | Kibera (left) and Dagoretti (right) farmers profile – The flowchart shows sources and movements of pigs and the types of people involved. Notes: Categories of farm size appear as defined by the focus group discussion participants. Oval shapes colored yellow indicates commodities traded; arrows indicate the flows of products. The arrow width indicates proportional importance in terms of flow.

of this work was validated by presenting summaries back to stakeholders.

Data Analysis

Through listening to the recordings and reading of the notes, all the data from interviews and FGDs were collated into templates, following an approach outlined by Alarcon et al. (14). A template with different tables, each representing a section of interest, was completed for the analysis. This included their responsibilities, description of the chain (sourcing and selling of animals or products, transportation of animals, slaughtering processes, processing of the carcass, and distribution of products), important factors perceived by participants, interactions, rules governing their interactions, waste management and challenges. Data were entered by collating the information in the relevant sector and generating relevant codes. The creation of these templates was therefore a first analysis stage where potential themes were identified.

Mapping analysis of the pork system was done by carefully reading the templates to identify all the people involved, the products and places. Any interaction detected was plotted in a flow diagram. Mapping diagrams were constructed for each system segment: livestock keepers, Local independent abattoirs (LIA) and Integrated Company (IC). In the flow diagrams, people and places were represented by boxes and products by circles. Flows were indicated by arrows, and the width of these were used to indicate proportional contribution to the amount of products or animals movements in the system. When proportion of flows were obtained, this was indicated in the diagram. For clarity, only key people involved directly in the movement of pigs and pork products were introduced in the flowchart. Other stakeholders, such as regulators (e.g., meat inspectors) were left out from the mapping diagram to facilitate the readability of these. The abattoirs were coded for anonymity purposes, as abattoir A, B, C, and IC.

Thematic analysis of the data was carried out using Microsoft Excel. For this, all the codes (and associated text) from the templates were entered, and subsequently were used to identify relevant themes that provide an indication or understanding of the governance, challenges and food safety or disease practices for each node in the system.

Descriptive analysis of data from the movement permits was done to extract proportions of origin from different sources to the abattoir and to create Lorenz curves that indicate the amount of pig supply covered by each percentage of traders. For this, traders were coded as numbers and sorted according to the quantity moved. A Gini coefficient was then calculated to measure the equality of trade amongst pig traders.

RESULTS

Value Chain Mapping

Pig Farmers in Dagoretti and Kibera

Figure 1 shows the value chain mapping associated to pig farmers in Kibera and Dagoretti. In Dagoretti (peri-urban), participating pig keepers reported to have between 1 and 10 sows per unit (median = 7), while in Kibera (informal settlement) a pig keeper had about 1–3 sows per unit (Median = 2), with some occasional larger farms. In Dagoretti, people beginning pig farming purchase male and female weaners or growers at an age of 1–5 months. In medium to large farms, replacement is done by purchasing pregnant sows from farms owned by the IC, while small scale farmers bought weaners from neighboring small-scale farms. In Kibera, pig keepers only sourced from neighboring areas due to high cost of transportation. Once purchased, the pigs are trekked into the farm. Renting of boars for reproduction was described as a widespread practice in both areas.

Feeding of pigs is done mainly with waste collected from nearby markets (i.e., vegetable and fruit peeling) and with swill from restaurants. In Dagoretti, farmers reported that they supplement these feeds with commercial feeds bought from the agrovet shops. Brewers' waste and weeds growing along the roads were additionally mentioned. Free range scavenging of pigs was the most common system in Kibera. The most common water source used was rivers and the surface water the pigs get when scavenging and around households.

Finishing pigs were reported to be slaughtered in Dagoretti at an estimated average age of 5 months and with an average of 49 kgs. In Kibera, finishing pigs were slaughtered at 10 months of age, weighing averagely at 98 kgs. The method of selling and distribution of pigs were different in both areas. In Dagoretti, most finishers were sold to brokers or trader who slaughter them in the LIA's. Fewer farmers were reported to periodically supply pigs to the IC in times of shortages. In Kibera, most finisher pigs are sold to butchers, brokers or private individuals (consumers). The pig is either slaughtered behind the butchery (meat shop) or slaughtered in the farm or home (home slaughter) and meat sold to consumers. The selling of the meat is usually advertised via printed brochures pinned at strategic places around the neighborhood.

Local Independent Abattoirs and Wholesale Meat Market

Of the three LIA, the oldest one started in 1952 as a duck slaughterhouse before converting to a pig slaughterhouse. The other two started in 1972 and in 2007. The main characteristics of these abattoirs are shown in **Table 2**. The value chain mapping of the three abattoirs are shown in **Figures 2**, **3**.

The abattoirs have similar operations in the following areas:

(i) *Supply of pig:* This is mainly organized by traders and butchers, and the large majority (estimated 70% of all pigs slaughtered) is sourced from small-scale pig farms in Nairobi and from nearby counties of Nairobi (Kiambu and Murang'a counties). A small proportion of pigs slaughtered originated from further away counties from western Kenya (28). Pigs were reported to be sourced from these areas mainly during periods of shortage in the former areas. Traders can be described as merchants who buy live pigs from brokers, or less commonly, from farms. Brokers were defined as merchants who act as the bridge between the farmer and the trader and did not normally own pigs but rather get a commission for connecting a traders and farmers. Traders reported to bring pigs from either indoor farms or outdoor scavenging pig farms. Once pigs arrive to the abattoir these are slaughtered and sold. **Figures 2**, **3** shows the different categories of traders, differentiated by quantity sold. No further specialization was reported. Participants working in these abattoirs also explained that these are open to anyone wanting to slaughter pigs, and hence households with pigs can also slaughter their animals in these LIA and take their carcass home for consumption or sale from home.

(ii) *Valuation method of live pigs*: Visual live weight estimation was practiced by traders/brokers in all the abattoirs. Some traders reported that pigs from Kiambu country were preferred because of higher meat quality and bigger sizes, compared to pigs from other areas. This allow the traders to sell the carcass at higher prices.

(iii) *Centrality of traders and butchers*: Traders pay the abattoirs for slaughter services and will then transport the carcass to pork butcheries and other traders in the city's markets, where the meat is sold to restaurants or consumers. Another important chain in these system was the one organized by butchers. These are defined as people working in or owning a retail butcher. They purchase the live pigs on the farm, slaughter them in the LIA and bring the carcass to their own butcheries.

(iv) *Seasonality:* In all the abattoirs, the high season for slaughtering was reported to be in the last quarter of the year, associated with school fees payment period at the beginning of the following year, festive and the important tourism season. The first quarter of the year was identified as the low season for sale as farmers start a new cycle of rearing pigs aimed at sales in the last quarter of the year.

(v) *Legal requirements:* Pigs brought to the abattoirs are required to be accompanied by movement permit certificates and "no objection" permits, when coming from a different district.

(vi) *Live pig transportation:* Use of motor vehicles represented the main transport mode in all the three LIAs and are organized and paid for by traders or butchers, who hire or own the vehicles. A pig transporter was reported to move on average 30 pigs per week, and the majority have other business to supplement their income. Trekking of pigs and transport through motorcycle was reported as a minor practice, but with more relative importance for LIA C. Other traders used motorcycles and a smaller proportion of traders transported on foot especially in LIA C.

(vii) *Distribution of products:* This was done mainly through hiring motorcycles, with a few traders owning cars or trucks with a meat box. In abattoir C, those traders buying smaller quantities of meat (7–10 Kgs) reported carrying the meat in gunny bags. The high season for slaughtering was reported to be associated with school fees payment period, festive and tourism season.

(viii) *Waste disposal:* Blood is disposed together with liquid waste into lagoons while solid waste is given or sold to crop farmers to be used as organic fertilizers. The abattoirs are dissimilar in the following areas:

TABLE 2 | Summary for the abattoir's characteristics.

Operational	Abattoir A	Abattoir B	Abattoir C	Integrated company abattoir
Level of classification of abattoir[a]	Class B	Class C	Class C	Export abattoir
Average number of pigs slaughtered/week	215	90	178	1,922
Proportion of contribution of pork going through the abattoir to Nairobi	10%	5.6%	0.8%	83.6%
Proportion of pork slaughter supplied to Nairobi (%)	70–75%	100%	20%	70%
Application of HACCP or ISO 22000:2005	✗	✗	✗	✓
Number of working days	6	6	7	6
Type of employees (majority)	Temporal	Permanent	Temporal	Permanent
Slaughtering mainly on orders	✓	✓	✓	No
Trekking live animals	Some	Some	Some	✗
Transport of live animals using Motorcycle	A few	A few	Sizeable	Trucks only
Maximum time in Holding pen (days)	1–2	5	1–2	Overnight
Abattoir workers	15 Employed by pig traders	3 Employed by the abattoir	? Employed by pig traders	>50 Employed by the abattoir
Infrastructure				
Lairage	✓	✓	✓	✓
Stunning area	✓	✓	✓	✓
Bleeding area other than stunning	✓	✓	✓	✓
Liquid waste management	Lagoons	Lagoons	Lagoons	Lagoons
Cold room	✗	✗	✗	✓
Chiller	✗	✗	✗	✓
Toilets	✓	✓	✓	✓
Condemnation room	✗	✗	✗	✓
Condemnation pit	✓	✓	✓	✓
Detention room	✗	✗	✗	✓
Changing room	✓	✓	✗	✓
Fences surrounding the abattoir	✓	✓	✓	✓
Water dip for vehicles	✓	✗	✗	✗
Running water/source of water	**Borehole water**	**Borehole and city county tap water**	**Borehole water**	**City county tap water and borehole water**
Cutting room	✗	✗	✗	✓
Gut room	✓	✓	✓	✓
Clean offal area	✗	✗	✗	✓
Packaging area	✗	✗	✗	✓
Meat inspection office	✓	✓	✓	✓
Equipment				
Dehairing	With knifes	With knifes	With knifes	Machine
Scalding	Pouring hot water with pipe	Pouring hot water with bucket	Pouring hot water with bucket	Scalding tank
Singeing (torch)	✗	✗	✗	✓
Boilers	✗	✗	✗	✓
Incinerator	✗	✗	✗	✓
Stunning system	Electrical	Electrical	Electrical	Electrical
Workers uniform	✗	✗	✗	✗
Belt for knifes	✗	✗	✗	✓
Aprons	✗	✗	✗	✓
Footwear (boots)	✓	✓	✓	✓
Carcass dressing system (rail, cradle, floor)	Floor	Floor	Floor	Rail and Mechanized
Wash basin for workers	✓	✓	✓	✗

(Continued)

TABLE 2 | Continued

Operational	Abattoir A	Abattoir B	Abattoir C	Integrated company abattoir
Washing areas	✓	✓	✓	✓
Scale for carcasses	✓	✓	✓	✓
Hand soap in toilets	×	×	×	✓

[a] *Slaughterhouses are classified in category A, B, and C. Category A are those large slaughterhouses with throughput exceeding eight units of small pigs or 15 units of porkers or 30 units of beckoners, with a land size of larger not < 2.5 hectares, and are authorized to supply meat to any part of the country. Category B are medium size slaughterhouses with throughput exceeding 1–7 units of small pigs or 2–14 units of porkers or 4–29 units of bacon pigs, with a land size not < 1.5 hectare and are authorized to supply meat to its locality, towns, urban centres, or municipalities within 50-km radius. Category C are slaughter slabs with throughput not exceeding 6 unit of small pigs or 2 units of porkers or 1 unit of baconer pig, land size not < 0.5 hectares and are authorized to supply and serve the town centre, urban centre and areas where the facility is located (27).*

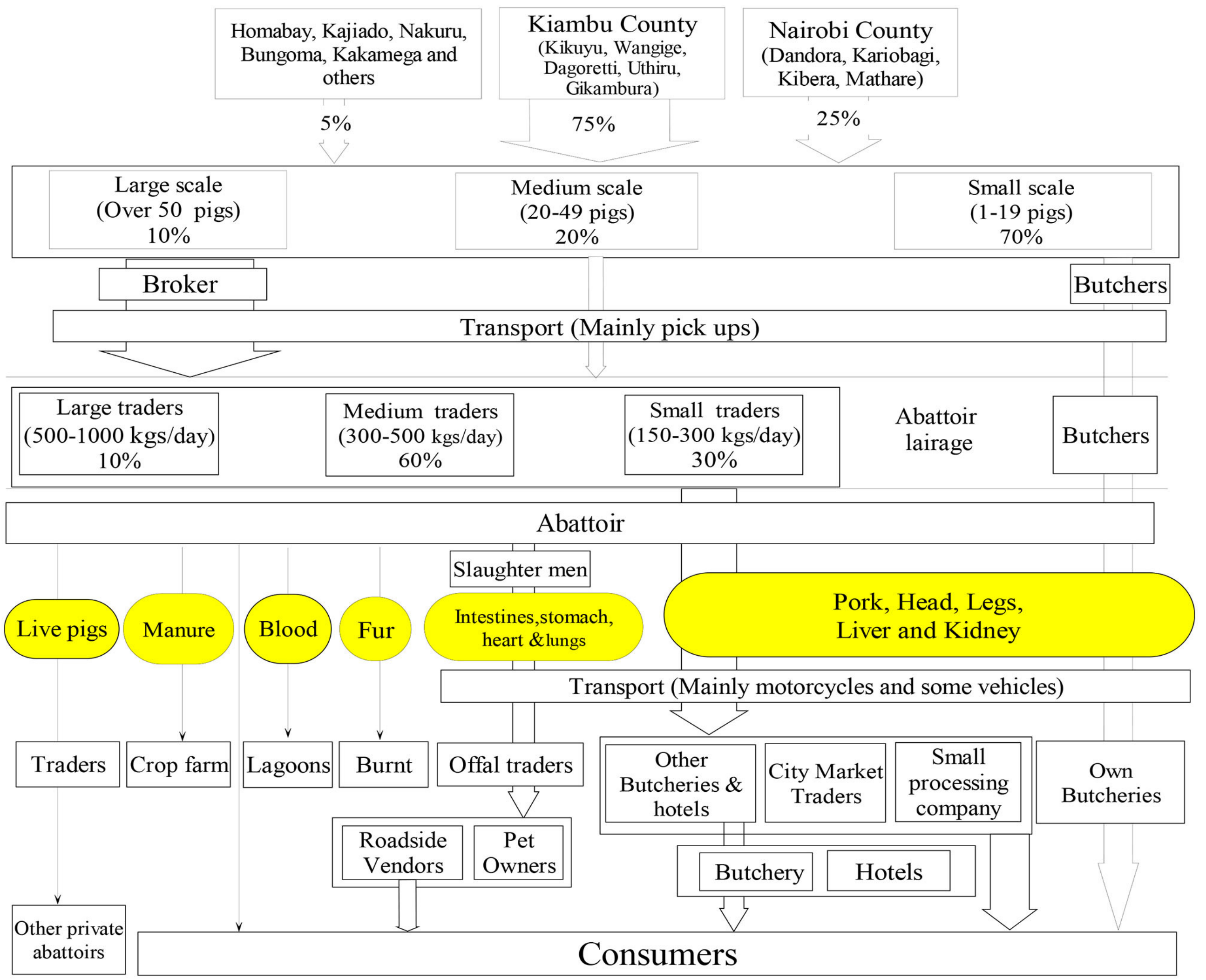

FIGURE 2 | Profile of people and product traded by abattoir A. Oval shapes colored yellow indicates commodities traded; arrows indicate the flows of products. The arrow width indicates proportional importance in terms of flow.

(i) *Live pigs trading:* While in abattoirs A and B, no trading of live pigs was reported in the lairage, in abattoir C, farmers were able to bring pigs in the lairage and sell them to either traders, brokers, butchers or other farmers.

(ii) *Distribution of offals:* Offals are given as payment to the slaughter men in abattoir A and C. Offals from Abattoirs A and C are then sold to specialized traders and roadside vendors operating in Nairobi informal settlements and neighboring counties

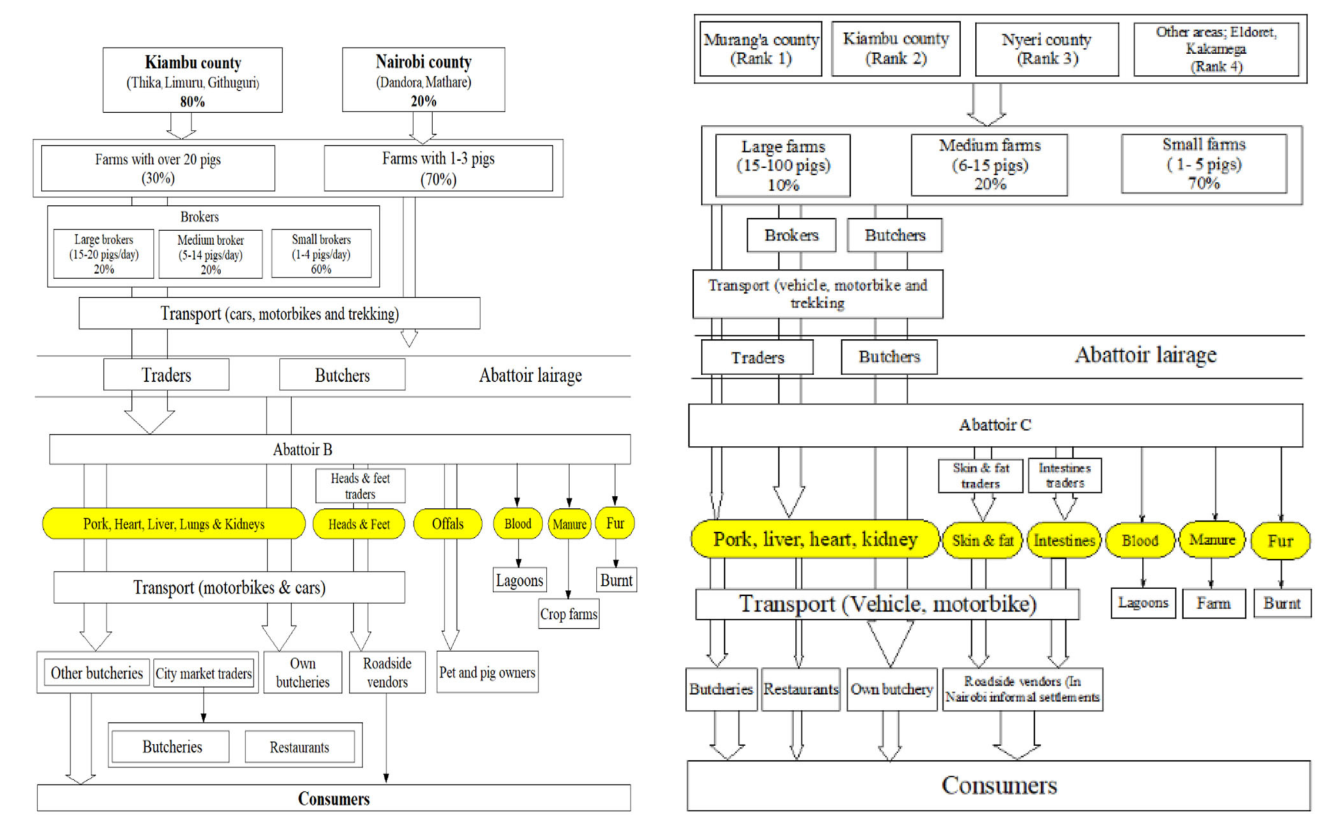

FIGURE 3 | Profile of people and product traded by abattoirs B and C. Oval shapes colored yellow indicates commodities traded; arrows indicate the flows of products. The arrow width indicates proportional importance in terms of flow.

such as Kirinyaga, Murang'a, and urban informal settlement of Nairobi and Thika, respectively. Offals (the intestines) from abattoir B are also given for free to pig farmers as pig feeds and pet owners in areas around the abattoir.

(iii) *Removal of fat from the carcass:* In abattoir B, the fat layer of the skin is removed and sold separately to specialized traders who sell them to roadside vendors in Nairobi informal settlements. In abattoir A and C, this is sold together with the carcass.

(iv) *Geographical distribution of products:* Although these abattoirs are classified as classes B or C, meaning that their meat distribution should be limited to local areas (27), distribution was reported to cover distant areas. In abattoir A, about 75% of pork is sold to Nairobi County (with city market receiving 12 pig carcasses per day), 10% to Kiambu county, 5% to Nakuru and Naivasha and the remaining 10% shared equally between Kajiado and Machakos counties. Abattoir A was therefore mentioned as the key supplier of the pork to City Market. In abattoir B, almost all butchers had their retailer business located in Nairobi County. About 60% of the pork from abattoir C is distributed to areas in Kiambu County, while 20% is distributed in Nairobi, 10% in Murang'a County and the remainder is distributed to other places such as Machakos, Nyeri, Nakuru, Kinangop, and Nyandarua.

The City Market, situated in Nairobi central business district, is a retail meat market dealing with beef, goat, mutton, pork, fish, chicken meat and rabbit meat. The market is owned and managed by the Nairobi County Government. They collect revenue from traders operating in the market. There are 4 pork stalls in the market with each trader selling an average of 7 carcasses a day, with an average carcass weight of 50 kgs. It was reported that 75% of the pork supply to this retail market comes from abattoir A, while 20% of the pork comes from Abattoir B and the rest (5%) comes from other unknown sources. About 55% of the pork in this market is sold to private individuals (consumers), 40% is sold to restaurants in and around the central business district, and the rest is sold to other places or people coming to the market.

Integrated Company

Figure 4 shows the value chain mapping of the IC. The company was founded in 1980, with the central purpose of selling fresh and processed pork products to all income groups in Kenya. The core business for this company is the production of fresh sausages, bacon, ham and pork, and with beef also becoming an

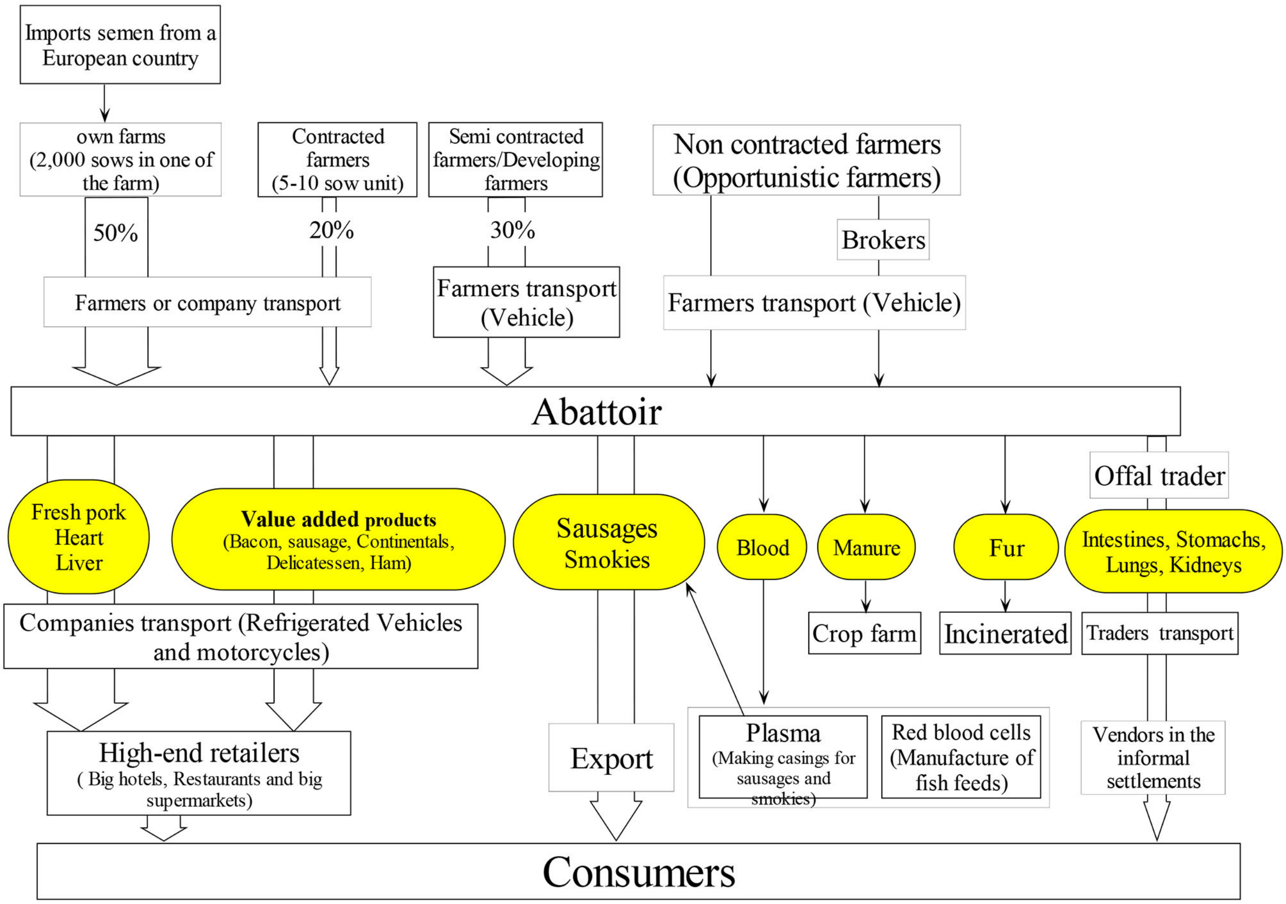

FIGURE 4 | Integrated Company (IC) profile: The flowchart shows sources and flows of pig and pork meat in a nearly fully integrated production system. The IC has owned farms that produce 50% of their throughput with the rest being supplied by contracted and semi contracted farmers. Notes: Oval shapes colored yellow indicates commodities traded; arrows indicate the flows of products. The arrow width indicates proportional importance in terms of flow.

important product (in a separate abattoir facility). In the mid-1980's, the company expanded into pig production, setting up a new butchery complex. The integrated company is the biggest supplier of pork products to Nairobi, and it markets through the abattoir 83.6% of Nairobi's supply followed by LIA which supply about 10% (these estimates do not include supply of pork that is distributed through backyard slaughter or from small slaughter slabs). The company reported that it operates with an ISO 22000:5000 certified export type abattoir, with a high level of mechanization, a relatively large, permanently employed work force, who are provided with continuous training. Their abattoir is well-equipped and includes veterinary inspection of pigs and of carcasses.

The IC reported to use four main sources for the supply of pigs. About half of its pig supply at the time of the study originated from their own large farms, composed of three units and with one of the farms having up to 2,000 sows. These farms imported their genetics from European countries. The other supply originates from "contracted farms," "semi-contracted farmers," and "non-contracted farmers." The main breeds brought for slaughter were large white, Landrace and their crosses, and most animals originated within a radius of 70–100 km from the plant. The main source areas were Murang'a, Ngong', Ruai, Dagoretti, and Kikuyu. Transport from the company owned farms and the contracted farms was organized by the company using its own trucks. For semi-contracted farmers, they can either request the company to transport their pigs or they can organize their own transport and get a reimbursement. The non-contracted farmers would organize their transport to the company abattoir plant.

Pigs are brought to the abattoir a day before slaughter, to allow them to rest overnight. Characteristics of the abattoir are shown in **Table 2**. Meat is processed into several value-added products, such as sausages and smokies (low cost sausages destined for the mass market). Fresh pork is vacuum packed or with food grade wrappers. Fresh pork, some value-added products and the heart and liver of pigs, are sold to high end retailers, such as big hotels (4 and 5 star), large supermarkets, high class restaurants and guest houses. Only a small proportion of these are sold to butcheries. It was estimated that about 70% of pork and pork products are sold in Nairobi County, with the rest sold to other parts of the country and exported. The offal, which included lungs, intestines, kidneys and stomachs, are sold to independent traders who sell these to roadside vendors operating in Nairobi informal settlements. The company owns over 140 refrigerated vehicles that are used to distribute their products.

Governance Factors and Challenges

Tables 3, **4** shows all themes associated to governance and challenges, as reported by the different stakeholders interviewed.

Governance Issues and Challenges Reported by Farmers in Dagoretti and Kibera

Governance themes were related to government interaction, producers' relationships and gender differences. In terms of interaction with the government, farmers and key informants complained that conflicting policies and laws exist whereby some city by-laws outlaw farming in the city while some officials still support urban agriculture. This creates confusion and makes farmers perceive themselves as outlaws, despite government employed meat inspectors, who offer services at all the registered slaughterhouses. Furthermore, they also felt that the government was responsible for the current shortfall in capacity of pig slaughterhouses in the area, which has contributed to some people practicing home slaughter. In some instances, particularly in Dagoretti, a meat inspector could be called to inspect carcasses that have been slaughtered at home. In Kibera, chiefs, who are local administrators in charge of lower level of administrative units – location, played a key role in arbitrating disputes involving crop farmers and farmers in instances that the scavenging pigs could stray and destroy farms.

In terms of producers' relationships, farmers reported that they did not have an association and that they operate independent of each other. The farmers depended mainly on brokers and traders – with whom they have short term relationships - to buy their pigs and transport them to slaughterhouses. Additionally, the perception of the farmers is that the IC controls the pork market and sets the pricing of pig and pork products. In terms of replacement of animals, the main characteristic considered for determining the best quality trait, is the litter size of the sows. Men were reported to dominate the ownership of farms in Kibera and Dagoretti. Women were responsible for cleaning and taking care of pigs. Some participants mentioned women owning large farms in Dagoretti. Farmers recognized that the image of roaming pigs in waste pits around the city discourages consumption of pork among the people who associate all pigs as being dirty and therefore unfit for consumption.

The main challenge of Kibera farmers was the lack of capital and land to enable them to expand their farms. The diminishing land sizes often lead to conflicts with crop farmers when the pigs are unconfined. Access and availability of feed was also an important challenge. Many small-scale farmers in both areas reported a dependency on market waste and on scavenging to feed their pigs, because commercial feed was too expensive for them. It was said that stiff competition among farmers for the collection of market waste exists. Diseases were also reported to be a challenge. Dagorreti farmers pointed out that the main diseases in the area were parasitism, pigs developing red spots (likely to be swine erysipelas) and a disease that caused pigs to die suddenly (likely to be African swine fever – ASF). In Kibera, parasitism was reported as the main disease challenge. In Dagoretti, lack of knowledge and training on pig feeding and on general and health management were reported. Other challenges identified include lack of market access to sell pigs and the theft of live pigs.

Governance Issues and Challenges Reported by Stakeholders Operating in LIA

Government interaction was mainly related to the collection of tax and ante- and post- mortem inspection of animals and carcasses. Traders and butchers opined that multiple licenses were needed to operate and that high taxes levied on them were making them uncompetitive. They attributed these changes to the "devolution system of governance." The licenses required for them to operate included those issued by the Ministry of Agriculture and Fisheries, the National Environmental Management Authority (NEMA), and the county governments. A government appointed meat inspector offered ante- and post-mortem meat inspection services ensuring that the meat sold to consumers has been passed fit for consumption. Furthermore, meat inspectors offered on the job training to the workers mainly on areas of hygiene. The traders are required to pay the slaughterhouse owner a fee, a government levy as well as pay the workers for slaughtering. The payment to the workers would be by cash while in abattoir B, the worker would be paid using offals.

Some of the main challenges reported by traders and brokers were related to higher price of buying live pigs occasioned by increased cost of production, further aggravated by the instability of pig and pork products prices. Apart from the dominant role of the large processing company, prices were said to be affected by high taxation of commercial feeds, which increases the cost of production and discourages its use. Further, the traders and brokers cited the high cost of pig transportation either from farm to slaughterhouse or from farm to farm searching for more pigs. They felt that a live pig market could reduce this cost by creating an exclusive central point to trade on. Diseases such as African swine fever limited the supply of pigs while limited access to artificial insemination limits the capacity to develop and upscale up pig farming enterprises. The continued use of natural breeding leads to reduction of the genetic pool of pigs and subsequently limits production potential of pigs. Traders felt this was one of the causes for the generally low weight of pigs.

In addition, traders and brokers attributed the low demand for pork products to the negative cultural perception toward pigs by some tribes and religions living in the city. Also, it was believed that consumers had major food safety concerns fuelled by the images of scavenging pigs in the city waste pits.

The abattoir owners also reported challenges related to the high cost of running the abattoir. This was believed to be aggravated by the stiff competition offered by the large processing company, the lack of access to capital to equip the abattoirs to the required standards, and the difficulties associated with

TABLE 3 | Governance themes and challenges reported by pig farmers and by stakeholders working in the LIA in Nairobi.

	Governance themes	Challenges	
Dagoretti and Kibera farmers	Government interactions: • Carcass inspection by government vets for pig slaughtered at home (Dagoretti) • Lack of inspection at home slaughter (In Kibera and sometimes in Dagoretti) • Perception of being outlaws • Area chiefs solves disputes between pig and crop farmers in Kibera • Conflicting policies • Lack of pork abattoirs generates reliance on home slaughter Producer relationships: • Lack of association • Dependent on brokers and traders for selling • Transportation cost incurred by brokers and traders • Feeling the pork market is controlled by a large company • Dependency in market swill /waste/ scavenging (small keepers) • Litter size is the main trait use for replacement of sows • Lack of written contracts Gender and consumers issues: • Male dominated activities except in large farms – Women only involved in cleaning activities • Scavenging pigs discourages consumption of pork	Kibera Farmers: • Lack of capital (Rank 1) • Sourcing for feed (Rank 2) • Diseases (Rank 3) • Diminishing land sizes (Rank 4) • Knowledge (Rank 5) • Conflicts with crop farmers (Rank 6) • Theft/insecurity (Rank 7)	Dagoretti farmers: • Lack of training: Feeding, Management and Health • Market access: Lack of contracts with brokers • High cost of commercial feeds • Lack of proper housing • Diminishing land sizes: To keep pigs and manure disposal
Local independent abattoirs	Government interaction: • Devolution- Increase of abattoir charges • Training carried out by meat inspector • Abattoirs charges include: Ministry of livestock, NEMA, City council, Ministry of public health and food hygiene certificates Producer relationships: • Market dominated by IC who sets prices • Farmers trust more the IC than traders when selling • Perception of trader's dominance in the system and sets prices at the abattoir level • Lack of grading of carcasses • Dependency on motorbike for transport of pork • Purchase depends on visual weight estimation • Preference to buys pig from small and medium scale farmers due to low prices • Disagreement on visual weight estimation is resolved by using live carcass weight • Lack of communication between MI, traders, butchers and farmers • Abattoir owner helps in solving disputes • Free holding ground used to attract traders Gender: • Male dominates the pork abattoir business while offal trading business is dominated by women	Traders and brokers: • Inbreeding due to lack of AI • Price instability – IC setting the market prices • Negative cultural perception of pork • Feeds taxation • High cost of transportation • Diseases –Reduce supply of pigs • Backyard slaughtering creating unhealthy competition • Lack of markets for live pigs' traders • Deception of pigs' sizes by farmers • Low weight due to poor feeding • Bad debts – Caused by butcheries • Pigs dying at the lairage of abattoir • Bad perception of pork due to scavenging	Abattoir owners: • Low supply of pigs due to high taxation on feeds • Legal issues when upgrading from slab to abattoir • Lack of capital to purchase equipment's • High cost of running the abattoir • Competition from farmers choice • Power outages • Traders conflicts Meat inspectors: • Poor transportation delays slaughter process • Arrogant workers/lack of awareness/PEP • Alcoholism • Conflict among workers • Lack of enough water • Lack of movement permits especially on Sundays • Early working hours • Pressure from traders to inspect quickly

TABLE 4 | Governance themes and challenges reported by the Integrated company, and by public health officers in relation to Nairobi pork retailers.

	Governance themes	Challenges
Integrated company	Government interactions • Meat inspectors provide ante and post-mortem inspection services • Government is charge of disease control in the country which affects pig production. • National Environmental Management authority (NEMA) periodically test water quality at the plant and inspects the environment for compliance • Uses IC as demonstration centres by government institutions such as universities Producer relationship • Third party producers supply feeds to distant farmers selling pigs to IC • Contracted farmer required to have at least a 5-sow unit • Contracted farmers offered company feeds, information, veterinary care, and advice • Semi contracted farmers have a long-term relationship but operate without a written agreement Customer/consumer relationship • Kenya is the main markets of the pork products produced • Brand all their products • Depend on traders to purchase offals (except) heart and liver • Supply storage facilities to their customers selling their product • Offer and provide training to customers selling their products	• High cost of power • High feeding cost –High taxation • Inconsistent contracted farmers • Lack/uneven of policy enforcement • Seasonal shortages • Price changing is difficult • Cold chain breakdowns along the value chain • Unfair competition practices; cross selling • High cost of product distribution • Poor cooking skills mainly by consumers • Poor infrastructure; bad roads
Retailers	• No association • Rely on traders for pork supply • Butcheries dominate in the low and middle end retailing levels • Major supply to butcheries is from LIA • Market sensitivity to pork • People do not like pork • Poor pork image due to scavenging and superstition • Men dominate retailing • Lack of written contract with suppliers	• Infrastructural challenges • Financial constraints • Too much regulation • Too many licensing required

bureaucracy involved in upgrading the abattoir from one class to the next, a change that would open new markets. Conflicts with traders and butchers over adherence to official and private standards was also reported as a challenge by abattoir owners. The low supply of pigs being brought for the slaughter at the facility, was attributed to the "prohibitive" taxation regime on the pig feeds in the country. Traders therefore implied that the high cost of feed limits production capacity and act as a barrier to entry for new farmers to enter the system.

The meat inspectors reported that ignorance among butchers, traders and other workers was the main challenge to their execution of their mandate. They attributed the ignorance to lack of awareness of official slaughterhouse rules and regulation. Alcoholism among workers was said to contribute to rule breaking. Other challenges, related to the fact that abattoirs start operating at very early hours and the pressure from poor transportation network around the city, which can delay their arrival and, consequently, the slaughtering process. Pressure from the butchers to hasten the inspection processes for them to quickly transport the meat to the retail point was another challenge mentioned. Slaughter on Sundays was said to pose a challenge as to the traders' transport of pigs without any movement permit because government offices are not opened over the weekend.

Governance Issues and Challenges Reported by the Integrated Company

The government provided ante and post-mortem meat inspection service. They were perceived as a critical element in the supply and movement of pigs to the IC. The IC managers reported to be satisfied with status of porcine disease control in the country. The government provides requisite authorization to facilitate transportation of live animals to the slaughter facility i.e., a letter of "No objection" and a "movement permit." NEMA conducts periodic water testing to ensure quality of water being used in the slaughtering plant and inspect the plant to ensure compliance with the environmental regulations of the country. Further, the government uses the IC slaughtering plant as a demonstration training plant for students in various educational institutions.

The IC has three types of suppliers. First, contract farmers who are characterized by having a written agreement with the company to supply a certain number of pigs periodically. To become a contract farmer, it is required to have at least a 5-sow unit (but the average is 10 sows per unit) and to use the company feeds and other inputs, such as company veterinary care and advice. Secondly, semi-contracted farms have a long-term relationship with the company but are run without any written agreement. These farmers provide an important fall back plan in

TABLE 5 | Food safety or disease management practices as by various stakeholders in Nairobi pig value chains in Nairobi.

Node	Themes
Kibera farmers	Common diseases: Worms Dead pig disposal: Fed to dogs, Burying, Burning, Consumption Management of sick pigs: Sell to brokers, Restrict movement of pigs, Slaughter it at home Lack of observation of withdrawal period Poor pig husbandry – dirty environment
Dagoretti farmers	Diseases: Worms, Mange, Paralysis, Red spots on pigs and Sudden death Dead pig disposal: Burying, Burning Management of sick pigs: Call private vets, Government veterinarians, Seek advice from agrovets (drug store) Lack of observation of withdrawal period Poor pig husbandry – dirty environment
LIA	Lack of ante and post inspection (Researcher observation) Overloading of meat boxes (Researcher observation) Poorly maintained meat containers (Researcher observation) Long transportation of meat (Meat transporter) Carrying of smaller quantities of meat in unauthorized containers (Researcher observation) Pigs staying at the lairage for up to 2 days (Abattoir owners) Presence of cats and ducks (Researcher observation) Slaughtering on order due to lack of cold rooms (Meattraderandabattoir owners Lack of boilers Abattoir owners Lack of disinfection (Researcher observation) Washing of carcasses during slaughter (Researcher observation) Houseflies during rainy season (Researcherobservation,Meat traders) Low workers' wages creating rule scaping incentive (Meat inspectors) Meat handling with bare hands (Researcher observation) Some workers poor hygiene due to ignorance (Meat inspectors) Farmers selling sick animals to new and inexperienced traders (Tradersand brokers) Death during transport in hot seasons (Traders) Fractures during transportation (Traders) Lack of continuous training (Workers)
Intergrated abattoirs	Buying pigs mainly from contracted farmers ISO certified and practices HACCP Cold chain present Mechanized operations Use of treated water and regular testing Refrigerated transport Trains retailers
Retailers	Lack of cold storage Lack of running water Use of untreated water Lack of medical certificates Poor personnel hygiene Unclean butcheries Hanging carcasses for more than 2 days Lack of medical certificates

times of pig shortages. The principal requirement of these sets of farmers to bring pigs to the company were for pigs to be free from diseases, to be vaccinated against foot and mouth disease, to be reared in pigpens, fed on commercial feed and demonstrate a high biosecurity level. Finally, the "non-contracted farmers" represented a small or insignificant proportion of the supply. These are farmers or traders who bring pigs to the company without having any prior arrangement and are prominent mainly during certain times of the year when there is an increased demand for pork, or a shortage of animals.

Challenges reported by the integrated company were related to the cost of production. This included the costs required to ensure food safety and other legal standards. Yet, IC felt that there was uneven enforcement of regulation among other producers (i.e., informal sector, including LIA) by the government enforcement agencies. This generates the feeling that IC is more intensively regulated than its competitors, who are not following the rules as stringently as it is done in the IC thus creating an atmosphere of unfair competition from the competitors.

An inconsistent supply of pigs by farmers was reported to pose a challenge of planning. During high production peaks non-contracted farmers and semi -contracted farmers bring pigs to the IC. Other challenges included these reported by IC products distributors who mentioned challenges with maintenance of the cold chain due to power outages, refrigerator breakdowns and in other circumstance switching them off to lower the cost of electricity leading to shortening of the shelf life of the products.

Governance Issues and Challenges Reported About the Retailers

It was reported that most retailers operate independently, and no association or group was said to exist. Retailers were perceived to have to rely on traders for the supply of live pigs and/or carcasses. To transport carcasses to their respective outlets, the retailers close to the abattoirs pool their transportation needs. Many obtain their pork chiefly from the LIA in Nairobi. Butchers were, however, perceived to dominate the selling of pork in low- and middle-income areas of Nairobi. The high-end market was thought to be served by the large integrated company supplying mainly through supermarkets and high-end restaurants.

The pork retailing business was perceived to be dominated by men. It was felt that the pork business is sensitive due to the cultural and superstitions associated with pork, especially with the association of pork with witchcraft by some communities living in Nairobi, and the negative image that the roaming pigs portray around dumpsite in the city.

The challenges for retailers were associated with poor infrastructure in terms of physical buildings, availability of portable running water and lack of equipment, such as the cold chain facilities. This is chiefly due to poor access to capital for expansion. The numerous legal requirements and licenses to run a pork butchery were also perceived as an important challenge.

Food Safety Themes

The food safety and disease management issues are displayed on **Table 5**.

Several stakeholders felt that the industry is dominated by the one large processing company followed by pig traders, that they felt was responsible for setting the prices of pork. No major group was reported to operate in LIA, only independent stakeholders. However, the analysis of the certificates of transport in abattoir A for the months of November and December showed that, of the 103 traders that operated in this abattoir, 15% of them were responsible for supplying 50% of the pigs slaughtered (**Figure 5**). A Gini coefficient of 0.48 was obtained, indicating a medium to high inequality. Any business disputes were reported to be solved by the abattoir owners or manager. Farmers who sold pigs to IC, cited trust as the reason as compared to traders and brokers while these who sold to traders and farmers did so due to their quick form of payment.

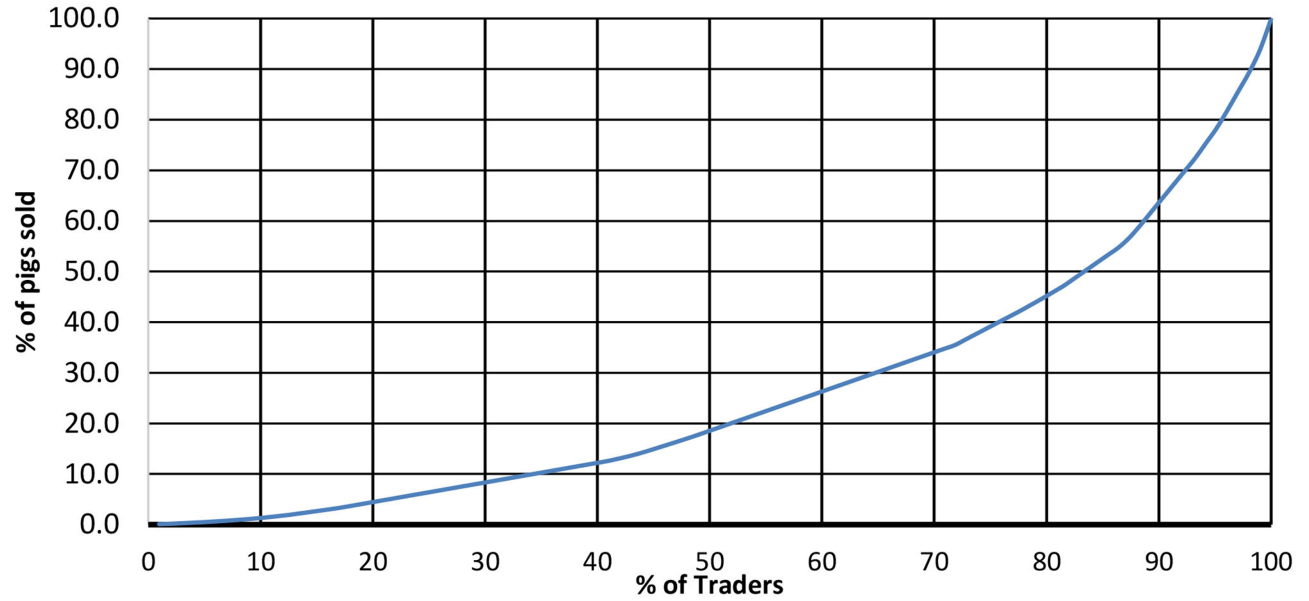

FIGURE 5 | Lorenz curve showing the proportion of supply to different proportion of traders within the less integrated abattoir A.

Traders perceived that consumers of pork did not demand quality, and hence no carcass grading or special cuts were necessary. Visual weight estimation caused cause disagreements between traders and farmers. The traders reported to prefer purchasing live pigs from small and medium farmers due to the perceived lower selling prices. The abattoir ownership, brokerage and trading were reported to be dominated by men, with the exception of the trading of offal, which was predominantly done by women.

Parasitism (worms) was reported as the main and commonest disease affecting pigs in both areas. While farmers in Kibera did not mention other diseases, farmers in Dagoretti described clinical signs of diseases that the authors believed to be African Swine Fever and/or Erysipelas. The signs described are reddening of areas around ears and abdomen, loss of appetite, and anorexia. When faced with diseases, farmers in Kibera reported to minimize losses by selling or consuming the pigs, instead of treating the disease (some reported to restrict the pig movements as a treatment option). On the other hand, Dagoretti farmers reported that they look for or pay for professional advice to treat these animals. Disposal of dead animals was done through burying or burning in both area. In Kibera these were used also to feed the dogs. During home slaughter, there is no meat inspector available, although some farmers in Dagoretti reported that inspectors could be invited to homes.

In LIA, the lack of equipment and structure for hygiene management at the abattoirs were observed (**Table 2**). In terms of infrastructure, the three abattoirs operate without refrigeration systems or condemnation and detention rooms. Two abattoirs did not have running water. Abattoir A uses a hose pipe to spray water onto the carcass, while abattoirs B and C use buckets to pour the water. One abattoir did not have a changing room for their staff. In addition, there was no clear demarcation between clean and dirty areas. In terms of equipment, workers lacked aprons and knife belts, and there were no boilers to clean the knives or any soap in the toilets. In two abattoirs lack of continuous training was reported, mainly since staff are employed on a casual basis, with high staff turnover. Several practices with potential to generate food safety risks were observed and reported. Low wages and lack of awareness were perceived to be the cause of many of these practices, particularly by workers in the abattoirs. Husbandry practices that include non-confinement of pigs and keeping the pigs in dirty areas were observed. Some pigs were reported to spend several days (up to 5 days in abattoir B) in the lairage awaiting slaughter. Pig brokers indicated that some farmers may sell off diseased animals to new/inexperienced traders, and that no drug withdrawal period is observed for pigs treated with antibiotics. Meat inspectors were reported to receive adverse pressure to quickly perform the ante and postmortem inspection, potentially leading to conditions not being identified.

The lack of a cold chain and the fact that many traders were reported to slaughter the pigs without having a customer order, meant that carcasses were exposed to ambient temperature for long periods of time until a customer for the meat is found. Although most carcasses are sold on the same day, it was reported that some stayed for up to 2 days hanging in the clean area of the abattoir. Overloading of meat boxes was reported to occur frequently, with the consequence that these boxes could only be partially closed, exposing the meat to dust and other possible environmental contaminants. Other themes associated to LIA are shown in **Table 5**.

The IC governance structure ensures that they control most activities; from slaughter to distribution of processed products;

Nevertheless, they reported that due to pig shortages, sometimes they buy pigs from non-contracted farmers, for whom they do not have control on the production process. For contracted farmers, they supply feeds, give health advice and monitor the production process including conducting periodic farm visits. The abattoir operation is fully mechanized and is ISO certified and applies HACCP principles thereby minimizing food safety risks. The cold chain is maintained throughout the process up to transportation of products to various outlets. At the outlets, they reported that they have challenges of ensuring maintenance of the cold chain mainly due to refrigerator breakdown or proprietors switching them off to lower the cost power especially at night. They have been conducting training with these outlets to ensure compliance with the cold chain (**Table 5**).

At the retail point, houseflies were reported to be a menace especially during the rainy season. The housefly could act as an agent to spread contamination. Many retailing points were reported to lack key infrastructure, such as running water or lack cold storage, with some meat hung for up to 2 days at ambient temperature. Most people working at the butcheries do not have medical certificates, mainly because of the cost associated with their acquisition. The long process involved in enforcing the public health regulations was reported as an impediment to ensuring proper sanitation among retailers (see **Table 5**).

DISCUSSION

The results obtained provide a detailed understanding of the flows and process of the Nairobi pork food system. Like all food systems the pork system supplying Nairobi is complex and requires strategic analytical approaches to determine factors and actors to whom interventions should be directed. Several studies have described how this can be achieved (14, 24, 29–31).

These findings highlight the large contrast in the operations between the organized formal sector dominated by the large processing company, and the rest of the sector based on LIA abattoirs or home slaughter. It is important to note that no slaughter slabs were visited in this study. These are believed to be few in number in Nairobi, as opposed to rural areas where they are more prominent (32). The differences observed between sectors represents important gaps that may seem difficult to overcome given the challenges reported on consumers' perceptions for pork. The small consumer population requiring high pork quality standards is mainly limited to high income consumers, and the size of the potential market is a barrier for more processing companies to emerge or for other sectors (i.e., LIA) to upgrade their operations. The mapping, challenges and governance results obtained in this study do however represent a baseline framework of current industry status and functionally, needed design policies and intervention aimed at formalizing the system or intervene in the informal system to improve food safety. In particular, it helps to provide the necessary context for the food safety issues reported and detected in the study.

Mapping results from urban and peri-urban pig producers show that while replacement was similar in both areas, selling of pigs presents some diversity and variation. In Dagoretti, a peri-urban area of Nairobi, most farmers reported to sell their pigs to brokers, traders and butchers who in turn slaughter in the abattoir. The use of abattoirs in this area could however be very much influenced by the proximity of one of the LIAs. In Kibera, farmers practice backyard slaughter more than in Dagoretti. The fact that no meat inspection is conducted in Kibera when conducting backyard slaughtering could represent a risk of exposure of pathogens to abattoir workers and local consumers, and Kibera, in this respect, is likely to be broadly representative of other similar settlements in Nairobi. Differences between urban and peri-urban sites were also observed in terms of pig feed, and their challenges, in terms of quality and lack of training, are similar to what was reported in Western Kenya where scavenging of pigs is predominant (18, 33). The type of feed has a bearing on the health status of the pigs and diseases are likely to be associated more with the scavenging pigs than with pigs kept indoors (3). Furthermore, low production efficiency can predominate with this type of feeding as was reported in a similar study by Gikonyo (34) where the main mode of feeding in peri-urban area of Nairobi (Thika) was largely scavenging in nature.

In the LIAs, the key group of people with highest power in the chain were the traders and butchers. They ensure the supply to the abattoirs and provide a market for the farmers, especially small farmers, many of which keep scavenging pigs in informal settlements. As these informal pig keepers are normally unable to supply pigs to the integrated company, these abattoirs represent the most formal channel that these farmers can access, as little or no requirement is needed to supply pigs. For this, the study shows that brokers play an instrumental role of looking for pigs in the farms and either bringing them to the traders or calling the traders to pick them up. Similarly, the importance of these brokers and traders for the development of small-scale producers have been reported in an earlier study conducted in Thika near Nairobi (34).Furthermore, brokers, due to their experience, are also responsible for ensuring that unhealthy pigs are not bought, and are therefore an important target group for disease control. The mapping analysis also shows that these abattoirs operate with some levels of inefficiencies and important infrastructure and equipment gaps, creating potential challenges to control food safety risks. Lack of written contracts between farmers, traders and retailers operating through this system may represent a barrier to establish requirements and incentives for improve production, but also can generate financial uncertainty. This lack of formal agreement had been reported in a previous study conducted by the Nairobi city council (35) This, in combination with the lack of an adequate system for the valuation of pigs and carcasses, could also favor experienced traders and disadvantage pig keepers. This is similar to a study undertaken in rural western Kenya (36). In addition, the fact that in abattoir A and B workers were employed by traders and that their pay depends on the number of pigs slaughtered, could possibly lead to a conflict of interest on food safety practices as workers hurried to slaughter maximum number of pigs in order to get the highest amount of pay. This dominant position of these experienced traders implies that the capacity for system upgrade resides mainly on them, and less to producers, small traders or abattoir owners. Policies that can generate contracts between stakeholders and reduce this inequality may provide a solution to improve food safety and disease control.

This study identifies several potential food safety issues existing in these LIA, such as the lack of proper equipment (e.g., boilers or aprons); poor infrastructure, such as lack of cold and detention rooms; important risk practices, such as scalding done manually on the floor, use of untreated water and long distance meat transportation by motorcycle without refrigeration; all coupled with informal pig sourcing and poor traceability. The informal sector therefore requires significant changes and investment in infrastructure and equipment to improve biosecurity and hygiene practices. Yet these may currently be outside the financial capacity of stakeholders given that the chain is based on small pig keepers (and pig keepers operating in backyard or in informal settlements environments), low throughput abattoirs and directed to low income consumers. Furthermore, lack of major public and private incentives in the system represents a barrier to generate these changes. The dominant position of traders and butchers suggests that they may be the key stakeholders that could help create the necessary financial incentives for system upgrade. These abattoir system improvements must however be carefully designed to avoid pushing small scale farmers from this semi-regulated chain and forcing them to operate only in slaughter slabs or backyard slaughter. Some food safety risks were related to stakeholders' behaviors and the capacity of government officers to enforce food safety regulations. Indeed, recent research shows that about 8.7% of pigs reaching these abattoirs are positive to cysticercosis which was not detected by meat inspection (28). This at the same time represents an important barrier to high end markets. Increasing government officers' capacity is needed to help, through training and enforcement of regulations, improving pig management practices, disease treatments, biosecurity and ensure adequate pre and post inspection. The current training system operated by the IC could represent an example or opportunity for transferring skills to stakeholders in the informal sector. To augment the above measures, we further recommend the creation and implementation of a formal grading system that brokers and traders could use, training of people on technology of value addition, introducing pig weighing machines as opposed to visual appraisal, and promoting formal contracts between people could potentially help farmers and trader to get a better value for their pigs. Contract farming has been shown to have a positive impact in alleviating poverty (37). Further, It has been demonstrated that a 1% likelihood of participating in contract farming may lead to 0.6% increase in household income (38).

The integrated company was identified as the major supplier of pork meat, covering 83% of pork supply through abattoirs, and therefore creating a monopolistic system, especially toward the formal segment. The company is therefore likely to have a critical influence and control on the pig and pork system in Nairobi and Kenya, and in its upgrading capabilities. As mentioned, the study shows that there is a large difference between this IC and the LIAs. The IC has a well-structured and robust supply system, with majority (70%) based on own farms or other farms where written formal contracts are established and in which the company has control on pig feed and veterinary inputs through own inputs. Nonetheless, 50% of supply comes from small farmers (either contract or semi-contract farms), revealing the dependency of the whole pork food system (IC and LIAs) on small-scale producers (5–10 sow unit). These smallholders can be relatively inefficient, as small sizes do not allow for batch management and the benefits of economies of scale, such as access to breeding, markets or reduce labor and other costs. There are considerable market opportunities for pork producers to intensify production and apply modern systems of farm management. The differences between systems are also highly evident with modern slaughterhouse and effective distribution systems. These major differences represent a very important gap in investment, indicating a major barrier to entry to other competitors. However, the fact that the IC has such a large market share and that only three LIAs exists supplying Nairobi (and indeed the rest of Kenya) could also indicate that pork is consumed mainly by high- and middle-income urban consumers and that low-income households use alternative meat products. Indeed, a cross-sectional study of 200 Nairobi low income households revealed that 7.9% of these consumed pork regularly. That study show that reasons for eating pork was mainly because of taste, while reasons for not eating pork were taste, tradition and perception on hygienic standards (39). The large gap between the formal and informal sectors could also reflect the income inequalities in Kenya, with low income people demanding price over food safety.

Several limitations were present in this study. Many of the participants interviewed and in focus groups were selected by the livestock production officers and meat inspectors and or abattoir managers. We endeavored to minimize the selection bias by ensuring the participants were as diverse as possible, to achieve heterogeneity and therefore ensure that all chains are identified. Secondly, from a practical and logistical point of view it was not possible to meet all the people involved in the chains, due to the unavailability of some of the people and business time-pressure. This could have led to missing some information or failure to identify some chains. In addition, some data collected represent the perception of key informants or group of people, who might have been reluctant to disclose some of the chains used to avoid problems. However, these challenges were overcome by asking participants to say how other people in the chains operated and by interviewing different key people that have an overall understanding of the markets, such as the meat inspectors, and triangulating the information with them. There is nonetheless an information gap on the amount of pork that is supplied through informal slaughter slabs or backyard slaughter. This gap is mainly due to the fact that there is no consumption data at all available in Nairobi for pork outside of the systems we studied. Further research on pork consumption in the city should be undertaken to understand the extent of pork supply through these other informal systems.

In conclusion, this study has provided an understanding of interaction between people working in the abattoirs and markets and urban farmers in Nairobi. It characterized the chains to which the people of Nairobi both contribute and are exposed, as well as illustrating their governance and food safety challenges.

The findings have relevance to animal health and farming policy, as well as to food safety policy in sub-Saharan African urban settings similar setting such as Nairobi.

DATA AVAILABILITY STATEMENT

The original contributions generated for the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical approval for this study was obtained from the ILRI Institutional Research Ethics Committee (ILRI IREC) (project reference: ILRI-IREC2014-04/1). ILRI IREC is accredited by the National Commission for Science, Technology and Innovation (NACOSTI) in Kenya. Furthermore, ethical approval form the Royal Veterinary College ethical committee was also obtained (project reference: URN 2013 0084H). The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MM, DM, PM, JA, and PA collected, analyzed data, and drafted manuscript. PA, EF, MM, JR, and SG were directly involved in developing study design, writing of manuscript, and critically reviewed all manuscript drafts. All authors contributed to the article and approved the submitted version.

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Demand for *Taenia solium* Cysticercosis Vaccine: Lessons and Insights From the Pig Production and Trading Nodes of the Uganda Pig Value Chain

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Taenia solium cysticercosis disease remains a key challenge to the pig sector in low- and middle-income countries in sub-Saharan Africa, Latin America and South East Asia, resulting in both economic losses and public health impacts. The World Health Organization has ranked it first on the global scale of foodborne parasites. A One Health approach has been recommended for reduction of infection pressure and eradication in the longer term. A new vaccine TSOL18 (Cysvax^{TM}), applied in combination with oxfendazole (Paranthic 10%^{TM}), a dewormer drug has been developed and field tested for the control of *T. solium* cysticercosis, with high potential to break the disease cycle. It is however unclear whether the products can be marketed through a market driven approach, and if smallholder pig farmers would be willing to take up and pay for the vaccine–oxfendazole combination. A choice experiment methodology was used to assess the potential demand and willingness to pay for the vaccine—oxfendazole combination by Ugandan smallholder pig farmers, and demand for vaccinated pigs by pig traders. The results showed that farmers highly valued quality assurance attributes and were not keen on the vaccine if there were no associated returns in the form of premium price for vaccinated pigs during sales. They were willing to pay US$ 2.31 for the vaccine if it resulted in a premium price for vaccinated pigs. Furthermore, they preferred an accompanying vaccine viability detector as part of its quality assurance. The pig traders on the other hand preferred high carcass weight of pigs, potentially achieved by using oxfendazole. The results show that unless the pig market systems pay a premium price for vaccinated pigs, and quality assurance systems guarantee quality vaccine, uptake of the TSOL18 vaccine and oxfendazole by farmers through market mechanisms may be unsuccessful. The current pig marketing system does not reward food safety, the focus is mainly on carcass weight. Alternative delivery mechanisms for the vaccine through a mix of private–public investments needs to be explored, as the benefits of vaccinated pigs are societal and include reduction and elimination of neurocysticercosis in the long run.

Keywords: *T. solium* cysticercosis, TSOL18 vaccine-oxfendazole, choice experiments, pigs, Uganda

INTRODUCTION

Zoonotic parasites, such as *Taenia solium* cysticercosis are a key challenge to the pig sector in low- and middle-income countries in sub-Saharan Africa, Latin America and South and South East Asia, resulting in both economic losses and public health impacts. Despite its traumatizing health and socioeconomic impacts, *T. solium* cysticercosis has received little attention in terms of investments for control and elimination and is considered a neglected disease by The World Health Organization (1), despite being a potentially eradicable disease. WHO has ranked *T. solium* cysticercosis first on the global scale of foodborne parasites. Eradication of *T. solium* cysticercosis is deemed feasible, because there exists efficient intervention strategies which can interrupt the parasite life cycle (2). Yet, cysticercosis is still endemic in most countries of Latin America, Asia, and Africa. Hotez et al. (3) attributes this to the fact that it is a disease affecting the poor, referring to it as a "forgotten disease of forgotten people" which does not motivate governments to take the necessary measures. A One Health approach involving several efforts at the household, herd, community and national levels, by medical, veterinary, environmental, policy and social sectors has been recommended as the best intervention toward the control and eventual elimination of *T. solium* cysticercosis and taeniasis (4). However, the feasibility of delivery of interventions in whole or part through private or public sector investments remain unclear. This will largely depend on the context and circumstances of various countries.

Humans are the definitive hosts of *T. solium* and harbor the adult tapeworm. Infections result from ingestion of raw or undercooked pork infected with active *T. solium* larval cysts, resulting in taeniasis in humans (5). Pigs act as intermediate hosts, acquiring *T. solium* cysticerci, (the larval stage of tapeworm) in their tissue, through the ingestion of *T. solium* eggs shed in the feces of humans suffering from taeniasis (6). The pigs get infected by consuming the human feces or water or feed contaminated with tapeworm eggs from humans. Humans can also harbor the cystic stage in their tissue following ingestion of *T. solium* eggs through food, water, or surfaces contaminated with feces (7). The *T. solium* eggs develop into cysts in different body tissues with serious consequences resulting from cysts lodged in the central nervous system, a condition termed as neurocysticercosis. Neurocysticercosis leads to various neurological symptoms, most commonly epileptic seizures and chronic headaches.

T. solium is suspected to be present in all sub-Saharan Africa countries with a prevalence of 0–14% for human *T. solium* taeniasis and 0.68–34.5% for *T. solium* cysticercosis depending on the region, study population, and diagnostic technique used (8). Studies such as Assana et al. (9) and Gabriël et al. (10), among others, have shown that poor living conditions coupled with poor management of pig husbandry in rural communities in developing countries greatly contribute to maintain the life cycle of the parasite between humans and pigs. Yet, at least 80% of people with epilepsy in the world live in resource-poor countries where most of them are affected by neurocysticercosis (11). The risk factors associated with *T. solium* cysticercosis include low standards of personal hygiene, poor environmental sanitation with inadequate disposal of containment of human stool, poor pig management particularly widespread occurrence of free roaming pigs, lack of and/or inadequate meat inspection, absence of control measures at all levels of the market chain and general lack of knowledge (12).

Due to paucity of good quality data, very few studies have estimated the economic impact of *T. solium* cysticercosis both from the public health and agriculture sector perspectives. Economic losses in the public health sector are associated with human cysticercosis, particularly neurocysticercosis. Gabriël et al. (4) and Hay et al. (13) show that neurocysticercosis is responsible for 30% of acquired epilepsy in endemic areas. Praet et al. (14) reported an estimated total annual cost due to *T. solium* cysticercosis of over 10 million euros resulting from direct and indirect losses, mainly from neurocysticercosis in west Cameroon. Other studies such as Murray and Lopez (15) in their estimation of the Global Burden of Diseases show that 503,000 Disability Adjusted Life Years (DALYs) were related to cysticercosis in 2010. The losses in the agricultural sector are largely due to reduced value of infected pork and carcass condemnation. Zoli et al. (16) estimate annual losses due to *T. solium* cysticercosis in 10 western and central African countries to be more than 25,000,000 Euros. Annual losses due to *T. solium* cysticercosis in Cameroon alone have been estimated to be a minimum of 2,000,000 Euros based on a loss of 30% of the value of the carcass (17). In most of the low- and middle-income countries, there is lack of well-organized meat inspection and official slaughter facilities, thereby partial or total condemnation of carcasses due to cysticercosis is rather exceptional and a high percentage of infected carcasses are marketed and consumed.

Over the past decade research has been undertaken to develop practical vaccines for use in pigs to prevent transmission of *T. solium*. A new vaccine TSOL18 (Cysvax^{TM}), applied in combination with oxfendazole (Paranthic 10%^{TM}), a dewormer drug has been developed and tested for the control of *T. solium* cysticercosis, with high potential to break the disease cycle. More recently, TSOL18 has been proven to be highly effective against naturally acquired infection with *T. solium* in pigs. Application of TSOL18 has been shown to be highly effective at complete elimination of *T. solium* pig infections during field trials when both primary and booster vaccines are applied in combination with oxfendazole treatment (18). Primary vaccination is given to pigs at least 2 months old, and the booster may be given 3 months after the primary vaccine. Oxfendazole eliminates the cysts that are already lodged in the pigs before vaccination and is also effective against other internal parasites and worms in the pig. Immunity in pigs develop within 2 weeks of the booster dose. In 2013, oxfendazole manufactured under Good Manufacturing Practice (GMP) standards was licensed for the first time for use in pigs to treat cysticercosis, while the TSOL18 vaccine was licensed in 2016 in India. Field trials to assess the efficacy of the combined use of the vaccine and oxfendazole in enhancing immunity against *T. solium* have been implemented in several countries including Uganda (19), Cameroon (20), and Nepal (21). Results from the trials have confirmed the efficacy of the vaccine and oxfendazole package. It is however unclear whether the products can be marketed through a purely market driven approach, and if pig farmers would be willing to take up and pay for the vaccine and oxfendazole package. Several studies, for example Karanja-Lumumba et al. (22), have shown that the propensity of poor, smallholder farmers to invest in preventative animal health treatments, even highly effective ones, may be very low, potentially undermining a purely market driven approach.

In Uganda, the pig sector has grown in the last decade. Demand for pork is increasing rapidly and the annual per capita pork consumption, at 3.4 kg, is the highest in East Africa (23). Fueled by the increasing demand, the number of pigs increased from 0.2 to 4.1 million between 1980 and 2018 (24). Most of the pigs are raised under smallholder systems characterized by poor husbandry practices. The prevalence of *T. solium* cysticercosis is high in several parts of the country. A field survey conducted in 2000 reported an average prevalence of 24% in five districts in the Lake Kyoga basin (25). However, in high pig density areas such as Masaka, Mukono and Kamuli districts, that are also characterized with better sanitation, prevalence is lower, estimated at 11–13% (26). We utilize a choice experiment methodology to assess the potential demand for the vaccine by the Ugandan smallholder pig farmers and their preferences for the technical and administrative attributes of the vaccine and oxfendazole package. We also assess demand for *T. solium* cysticercosis vaccinated pigs by pig buyers and examine the implications of the results on the delivery mechanism of the products through either public or private sector efforts. Both the TSOL18 vaccine and oxfendazole are not yet available for production in Uganda.

MATERIALS AND METHODS

Choice Experiments

The choice experiment framework used in this study is based on a multi-attribute stated preference method that assesses the value of single attributes of a bundled good such as a vaccine, by using individuals stated preference in a hypothetical scenario (27). Preferences are measured directly, and then related to utility, making it possible to estimate economic values of attributes of the vaccine and willingness to pay for vaccine options. Its theoretical framework derives from the Lancasterian consumer theory and discrete choice random utility theory (28). The vaccine attributes, and attribute levels are identified and combined according to an experimental design to create sets of discrete choice alternatives. Respondents are then presented with a series of choice alternatives and asked to choose their most preferred option. Each choice alternative is characterized by several attributes, one of which is a monetary attribute offered at different levels across alternatives. Analysts can then assess how respondents' choices change as the attributes and monetary amounts are varied. Appropriate models are then applied to the choice data to reveal a measure of utility for the attributes of the choices.

Choice experiments have been used in a few studies to assess decision-making by livestock keepers regarding vaccination of livestock to help inform vaccine development and policy. Bennett and Balcombe (29) implemented choice experiments to assess cattle farmers' attitudes to and willingness to pay (WTP) for a bovine tuberculosis cattle vaccine. Terfa et al. (30) employed a discrete choice experiment approach to elicit farmers' preference for attributes of Newcastle disease vaccination programs for village poultry systems. Other studies such as Railey et al. (31) examined household preferences for accurate and timely vaccine information delivered through diagnostic testing to inform which Foot and Mouth Disease vaccine to apply during an outbreak.

In this study, we applied the choice experiment at two levels. The first level focused on farmers preferred vaccine attributes and willingness to pay for vaccine options. The second level focused on pig traders' attributes for slaughter pigs and willingness to pay for vaccinated pigs. The traders purchase pigs for slaughter from farmers. The vaccine and pig attributes and

TABLE 1 | TSOL18 vaccine and oxfendazole attributes.

Attribute	Levels
A. Cost of vaccine which includes the cost of two doses of oxfendazole and TSOL18 vaccine	0. UGX10,500 (US$2.9) 1. UGX13,500 (US$3.8) 2. UGX18,000 (US$5.0)
B. Administration of vaccine which includes service fee for the veterinarian/animal health worker without including transport)	0. UGX2,500 (US$0.7) per pig—service fee for veterinarian or animal health worker who administers vaccine and deworming service to a group of 10 farmers 1. UGX4,000 (US$1.1) per pig—service fee for an animal health worker who administers vaccine and deworming service to one farmer 2. UGX6,000 (US$1.7) per pig—service fee for veterinarian who administers vaccine and dewormer to one farmer
C. Improved pig weight gain	0. Pig gains an extra 10% weight because other worms are killed by the dewormer 1. Pig gains an extra 5% weight because other worms are killed by the dewormer
D. Top up price premium for vaccinated pigs	0. 50% of market price 1. 30% of market price 2. 15% of market price
E. Frequency of vaccination to attain immunity	0. Once at 2 months old 1. Twice (one dose at 2 months old and another dose 3 months after) 2. Three times (one dose at 2 months of age, second dose 3 months later, and a third dose after another 3 months)
F. Vaccine viability detector	0. Non-inclusion of an indicator to test for vaccine viability 1. Inclusion of indicator that shows vaccine viability

Exchange rate: US$1 is equivalent to UGX 3600 during the study period.

TABLE 2 | Attributes for vaccinated pigs.

Attribute/Trait	Level
A. Top-up premium price due to *T. solium* cysticercosis-vaccinated pig	0. 5% top-up 1. 10% top-up 2. 15% top-up 3. 20% top-up
B. Market price of pig (average of a 40-kilogram liveweight pig)	0. UGX155,000 (US$43.1) 1. UGX200,000 (US$55.6) 2. UGX225,000 (US$62.5) 3. UGX250,000 (US$69.4)
C. Proof of vaccination	0. Producer's word 1. Certificate provided by a government veterinarian 2. Certificate provided by a private veterinarian 3. Vaccinated pigs are ear-tagged
D. Improved carcass weight gain	0. Pig gains an extra 15% carcass weight because other worms are killed by the dewormer 1. Pig gains an extra 10% carcass weight because other worms are killed by the dewormer 2. Pig gains an extra 5% carcass weight because other worms are killed by the dewormer

Exchange rate: US$1 is equivalent to UGX 3600 during the study period.

the associated attribute levels used in this study were identified based on previous studies and expert opinion. Six key vaccine attributes covering both technical, administrative features and effect were identified. The technical attributes were inclusion of a vaccine viability detector and frequency of vaccination to attain pig immunity. The vaccine viability detector is a monitor included on vials containing the vaccine and gives a visual indication of vaccine potency. The vaccine viability indicator attribute was identified as important in providing confidence to the users of the vaccine. The frequency of vaccination to attain pig immunity was identified as important as it depends on the period that pigs are reared on-farm, which depends on the type of production system practiced. Poudel et al. (21) indicate that primary vaccination is given to pigs at a minimum age of 2 months old and a booster vaccine given 3 months after the primary vaccine. Immunity develops within 2 weeks of the booster dose. Weaner pigs in farrow-wean systems may spend <5 months on-farm.

The administrative features of the vaccine were identified as the price or cost of the vaccine to the farmer and the vaccine administration cost. The vaccine effects were price premium for the vaccinated pigs and pig liveweight gain due to the oxfendazole de-wormer effects. The cost of the vaccine per dose was computed based on the manufacturer's cost of producing the vaccine, freight, insurance and delivery charges to the warehouse, transport costs to retail outlet, and a markup price by the retailing veterinary stockists. The administration cost of the vaccine included a service fee for the veterinarian/animal health worker without including transport. The vaccinated pig attributes for the traders' choice experiment included carcass weight gain, proof of pig vaccination, market price of pig and the premium price due to vaccination. For each attribute, two or three levels were identified as presented in **Table 1**.

Attributes associated with vaccinated pigs were also identified using the same process. Four key attributes were identified as presented in **Table 2**.

The identified attributes and the associated levels (farmer level survey) were combined based on a fractional factorial orthogonal main effects-only experimental design using SAS software (32). The design resulted in 12 generic vaccine choice sets, each with three alternatives and a "no-buy" option. The choice sets were used to construct choice cards with pictorial profiles describing the differences in vaccine attributes and levels to demonstrate each choice set to the farmer respondents. The 12 vaccine choice sets were blocked into two groups of six choice sets each. Each respondent was presented with six choice sets. **Figure 1** shows an example of a choice set option presented to the farmers.

The experimental design for vaccinated pig attributes (pig trader survey), also using a fractional factorial orthogonal main effects-only experimental design (SAS software), resulted in 8 choice sets, each with three alternatives and a "no-buy" option. The eight choice sets of vaccinated pigs were all presented to the pig trader respondents. **Figure 2** shows an example of a choice set option presented to the traders.

The overall efficiencies of the experimental designs were high; D efficiency: 98.6%; A efficiency: 97.1%; and G efficiency: 93.4%. The high efficiencies show that the designs are statistically efficient. The key consideration is that maximizing statistical efficiency minimizes the variability of the parameter estimates (33).

Implementation of the Choice Experiments

The choice experiment was administered as part of a short farm-level and pig traders survey questionnaire using in-person interviews. The surveys were conducted between November and December in 2018. The farmers survey tool included the choice cards with pictorial profiles describing the vaccine and pig attributes. The rest of the questionnaire covered socioeconomic aspects such as location of the farm and other household- and farm-level characteristics. The pig traders survey tool was similar to the farmers survey with the exception of some specific questions about the traders' business activities and their perceptions and attitudes regarding the role of various actors in the control of porcine cysticercosis.

The administration of the choice experiment was conducted in the following manner, the respondents were first asked if they were aware of *T. solium* cysticercosis, and its effects. They were then provided with a background on *T. solium* cysticercosis and its transmission cycle and health effects. They were also provided with information about the *T. solium* cysticercosis vaccine that may soon be introduced in the market in Uganda and the importance of feedback from pig farmers and pig traders to the vaccine manufacturer. They were then presented with the choice

FIGURE 1 | An example of a choice set option for farmers.

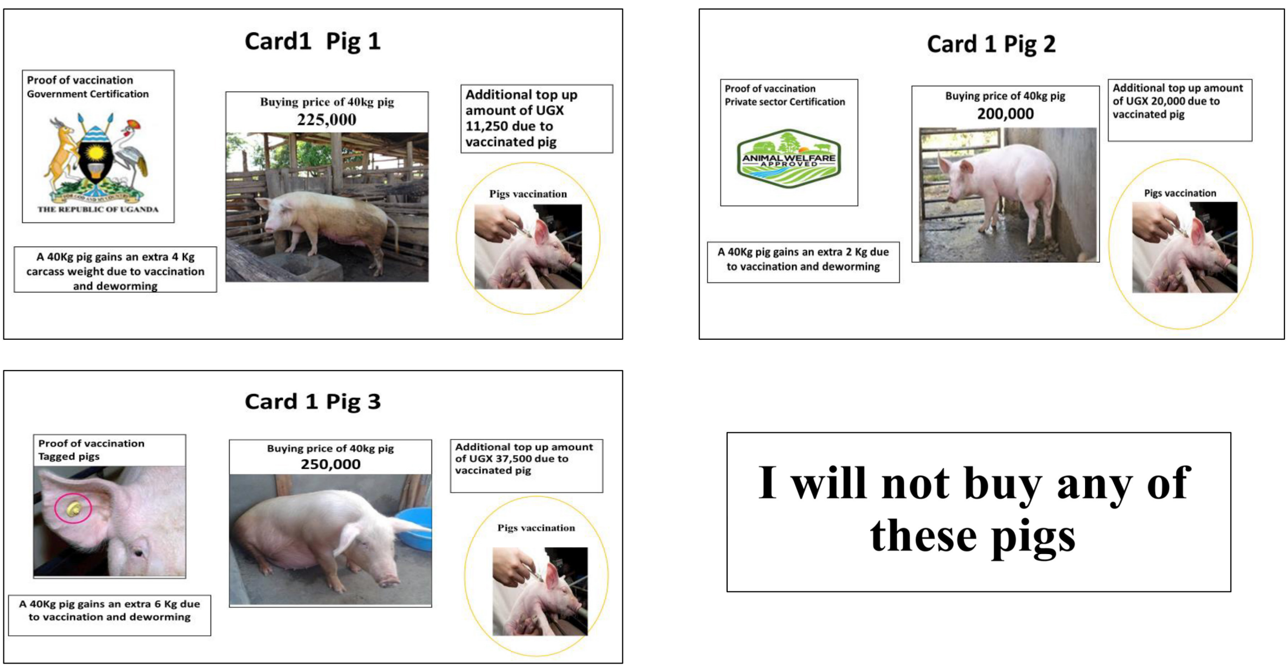

FIGURE 2 | An example of a choice set option for traders.

cards developed from the information in **Tables 1**, **2** in the form of pictorial profiles. The farmers were shown three vaccine choice options at a time for each of the six choice sets and asked to choose the most preferred vaccine option to purchase. Similarly, the traders were shown three choice options of vaccinated pigs for each of the eight choice sets. In each case, a "no-buy" option

TABLE 3 | Choice experiment variable coding.

Independent variables	Units and coding of the variable levels
Vaccine attributes mode	
Cost of vaccine	Cost in US$
Premium price	% top up of market price
Low vaccination frequency	1 = Once at 2 months, 0 otherwise
Medium vaccination frequency	1 = Twice in the life of the pig, 0 otherwise
High vaccination frequency[a]	1 = Thrice in the life of the pig, 0 otherwise
Weight gain	% of weight gain in the pig due to the dewormer
Vaccine viability detector	1 = Inclusion of a vaccine viability detector, 0 otherwise
Vaccine administration cost	Cost in US$
Vaccinated pig attributes model	
Market price of 40 kg liveweight pig	Price in US$
Top-up premium price	% increase due to pig vaccination
Proof of vaccination—private vet certificate	1 = Yes, 0 otherwise
Proof of vaccination—government certificate	1 = Yes, 0 otherwise
Proof of vaccination—ear tagging[a]	1 = Yes, 0 otherwise
Proof of vaccination—producer's word	1 = Yes, 0 otherwise
Improved carcass weight	% increase in carcass weight due to deworming

[a]*used as the base scenario in the model.*

was also presented for farmers and traders who preferred none of the three options.

Choice Experiment Modeling

A utility maximizing behavior is assumed, implying that the probability of a decisionmaker, *n* choosing vaccine choice alternative *A*, from a finite set of *j* alternatives in a choice set *k*, occurs if and only if it yields higher utility compared to any other alternative. This is depicted as;

$$P(A) = Prob\left(V_{nA}+\varepsilon_{nA}>V_{nj}+\varepsilon_{nj}\right)\quad A\neq j,\ \forall j\in k \qquad (1)$$

P(A): probability of choosing alternative A
V_{nj}: deterministic component of the utility
ε_{nj}: stochastic component of the utility

Rearranging Equation 1 yields;

$$P(A) = Prob\left(\varepsilon_{nj}-\varepsilon_{nA}<V_{nA}-V_{nj}\right) \qquad (2)$$

The distributional assumptions on ε leads to various choice models.

We used a mixed logit model using NLOGIT 6 econometric software to assess factors that influence choice and to estimate the willingness to pay for the vaccine attributes, the vaccine options and vaccinated pigs. From Equation 1, the utility associated with vaccine choice alternative *A* as evaluated by each individual decisionmaker *n* is represented in a discrete choice model by a utility expression U_{nA} of the general form;

$$U_{nA}=\beta_n V_{nA}+\varepsilon_{nA} \qquad (3)$$

Where V_{nA} is a vector of observed variables that includes the attributes of the vaccine and vaccinated pigs, and socioeconomic characteristics of the respondent, β_n is the taste coefficient vector associated with V_{nA}, for respondent *n* and ε_{nA} is an unobserved stochastic term that is assumed to be identically and independently distributed with a Gumbel distribution. The coefficients β, vary over respondents in the population with density *f*(β). The density is a function of parameters *Θ* that represent the mean and covariance of the β's in the population (28). The vector of random coefficients β can be expressed as the population mean and the individual specific parameter deviation from that mean. The decision makers know the value of their own β_n and ε_{nA} for all *j* alternatives and chooses alternative *A* if and only if it is greater than the other choice alternatives. Conditional on β, the probability that the decisionmaker selects alternative A results in the choice probability;

$$P_{nA}(\beta_n) = \frac{e^{\beta_n V_{nA}}}{\sum_j \beta_n V_{nj}} \qquad (4)$$

However, β_n is unknown to the analyst we therefore used the unconditional probability. The unconditional probability is the integral of the conditional probability in equation (4) over all possible values of β which depends on the distribution of β, that is unknown to the analyst. This takes the form of a mixed logit probability:

$$P_{nA} = \int \left(\frac{e^{\beta_n V_{nA}}}{\sum_j \beta_n V_{nj}}\right) f(\beta)\, d\beta \qquad (5)$$

We assumed a normal distribution for the taste coefficients, β. Since the integrals in Equation 5 do not have a closed form, it is simulated by taking draws of β from the population density *f*(β)|*Θ*. In this study, Halton draws, which yield much more accurate approximations in Monte Carlo integration relative to standard pseudo-random draws, are used (28). The implicit prices or willingness to pay (WTP) for the vaccine and vaccinated pigs attributes is estimated as the rate of change in the attribute divided by the rate of change of the cost attribute, also referred to as the marginal rate of substitution. This is represented as:

$$WTP_n = \frac{\partial U/\partial Z_{nj}}{\partial U/\partial P_{nj}} = -\frac{\beta_n}{\gamma_c+\gamma_a} \qquad (6)$$

P is the cost associated with the vaccine and includes both the cost of buying the vaccine and its administration cost, as represented by the coefficients γ_c and γ_a,

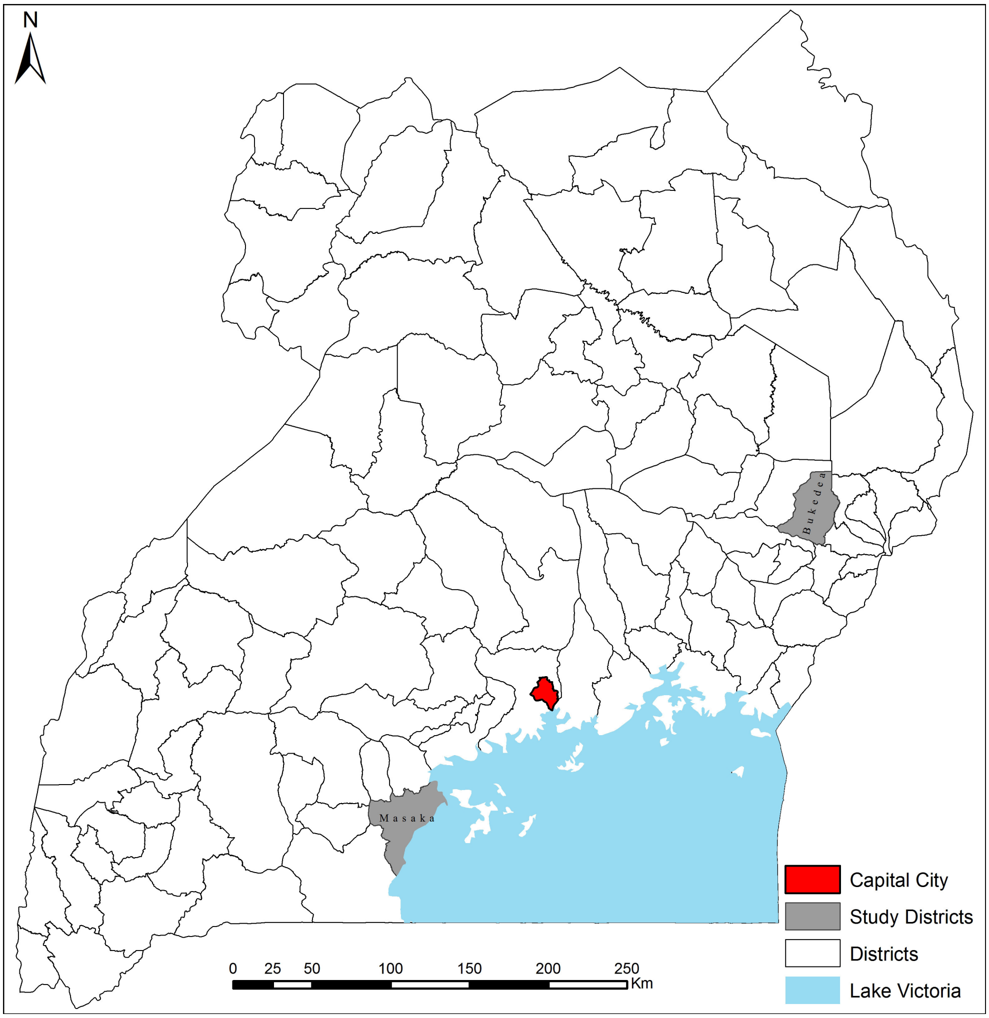

FIGURE 3 | Location of the study sites.

respectively. The confidence intervals of these non-linear functions of parameter estimates, was approximated using delta method.

The choice experiment variables used in the model and the coding of their corresponding levels are presented in **Table 3**. We employed dummy variable coding for the choice experiment variables to measure non-linear effects in the attribute levels. The dependent variable in the mixed logit model is a dummy variable showing the choice option selected by each respondent for any given vaccine or vaccinated pig choice alternative.

Study Area and Sample Size

The study took place in two districts of Uganda, Masaka and Bukedea (**Figure 3**). Masaka is in central region and was selected because it has the highest pig population density in the country. Several pig value chain projects also operate in the district. Bukedea is in the eastern region and was selected because *T. solium* cysticercosis vaccine trials were carried out by the Global Alliance for Livestock Veterinary Medicines (GALVmed) in the district[1]. Some of the pig value chain actors in Bukedea district were therefore aware of the vaccine. The selection of the two districts was therefore to leverage on existing information on vaccine trials and *T. solium* cysticercosis awareness.

A total of 294 pig farmers from Masaka and Bukedea districts participated in the *T. solium* cysticercosis vaccine choice experiment interviews. Forty eight percent of the farmers were from Masaka and 52% from Bukedea. Each farmer responded to six choice sets, yielding a total of 1,764 observed choices. A total of 33 pig traders from Bukedea district participated in the vaccinated pig choice experiment interviews. Each

[1]https://www.galvmed.org/new-tools-tackle-porcine-cysticercosis-rural-uganda/.

TABLE 4 | Pig traders' perceptions on practices and roles of various actors for control.

Statement	Level of agreement (% of respondents)				
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
I believe it is important to protect my consumers' health by ensuring that I sell *T. solium* cysticercosis-free pigs/pork	9.1	0.0	0.0	30.0	60.6
I condemn pork/pigs infected with *T. solium* cysticercosis	3.0	0.0	0.0	24.2	72.7
The market system should encourage farmers to vaccinate their pigs against *T. solium* cysticercosis by giving premium prices	3.0	0.0	6.1	69.7	21.2
I believe the *T. solium* cysticercosis vaccine + dewormer is the most effective option for controlling *T. solium* cysticercosis	0.0	0.0	6.1	51.5	42.4
I feel that control of *T. solium* cysticercosis is the role of the government and it should therefore subsidize the cost of the vaccine	3.0	12.1	3.0	39.4	42.4
Public health is the role of the government, not the pig traders	27.3	3.0	0.0	33.3	36.4
I do not care about *T. solium* cysticercosis-infected pigs because I don't consume them. The consumer is the one to care	66.7	33.3	0.0	0.0	0.0

trader responded to eight choice sets, yielding a total of 264 observed choices.

RESULTS

Awareness of *T. solium* Cysticercosis and Perceptions on Practices and Roles of Various Actors for Control

At least half of the pig farmers interviewed were aware of *T. solium* cysticercosis. Eighty percent of those who were aware of it were from Bukedea district. Their main source of information was the area veterinary officer or animal health assistant. Twenty-two per cent of the farmers in the overall sample indicated their pigs had suffered from *T. solium* cysticercosis in the last 24 months. This resulted in loss of pig income as most of the traders offered lower price for the pigs once they discovered the animals had cysts.

Eighty per cent of the traders surveyed indicated they had come across *T. solium* cysticercosis infected pigs. They recognize the disease mainly by lingual palpation, checking below the tongue of the pigs for cysts. Most of the traders, 94% indicated rejection of pigs suffering from *T. solium* cysticercosis, though during periods of pig scarcity they sometimes purchase infected pigs at lower prices. **Table 4** shows traders' perceptions about practices and roles of various actors on control of *T. solium*. The traders reported being concerned about consumers health and perceive the vaccine as the most effective control option. They however believe that controlling *T. solium* cysticercosis is the role of government and should therefore subsidize the cost of the vaccine.

Pig Farmers Attribute Preferences for *T. solium* Cysticercosis Vaccine

The mixed logit model results for the *T. solium* cysticercosis vaccine is presented in **Table 5**. We performed a likelihood ratio test using the conditional logit model estimates as the restricted model and the mixed logit model estimates as unrestricted. The chi-statistic $[\chi^2_{(12,\ 0.01)} = 26.22]$ with $p < 0.001$, showed a better model fitness with mixed logit, which allows for random taste variation.

The results indicate a strong statistical significance of the mean coefficients of some of the vaccine attributes including vaccine viability detector, administration cost of the vaccine, the cost of the vaccine and premium price of pigs due to vaccination. The model reveals preference for a vaccine that is not costly, has low administration costs, and has a vaccine viability detector integrated. There was also strong preference for the vaccine if farmers get premium price for the vaccinated pigs. Attributes associated with vaccination frequency and weight gain of pigs because of deworming were not statistically significant in the model. The model estimates on cost of vaccine and its administration cost had a significant negative coefficient, confirming the high propensity by farmers to hold onto money as they have high time preference for money.

Associated with each of the mean coefficient estimates of the random taste parameters are derived standard deviations calculated over the 100 Halton draws, indicating the amount of spread that exists around the sample population. The standard deviation of the random coefficient on vaccine viability detector was statistically significant ($p < 0.01$).

TABLE 5 | Mixed logit model estimates for *T. solium* cysticercosis vaccine attributes.

Parameter	Coefficient	Standard Error
Random parameters in utility functions		
Vaccine viability detector	0.734***	0.113
Vaccine administration cost	−0.255***	0.068
Cost of vaccine	−1.230**	0.525
Non-random parameters in utility functions		
Constant	2.627***	1.056
Squared cost of vaccine	0.000**	0.000
Premium price	1.741***	0.209
Low vaccination frequency	−0.156	0.110
Medium vaccination frequency	−0.114	0.082
Weight gain	−0.139	1.367
Heterogeneity in mean, parameter variable		
Vaccine viability: Bukedea	−0.218	0.135
Vaccine administration cost: Bukedea	0.118**	0.058
Vaccine cost: Bukedea	0.256***	0.051
Standard deviations of parameter distributions		
Vaccine viability detector	1.549***	0.526
Vaccine administration cost	0.109	0.146
Cost of vaccine	0.243	0.152
Likelihood ratio test[a]	72.35 ($\chi^2_{12,\ 0.01}$) = 26.22	
Log likelihood function at start values (MNL)	−2445.42	
Simulated log likelihood function at convergence	−2212.38	
Halton draws	100	
Number of observations	1,764	

****, **, and * denotes p-values 1, 5, and 10%, respectively.*

This implies that different individuals possess individual-specific parameter estimates for that attribute that may be different from the sample population mean parameter estimate. The standard deviations of the other random and non-random parameters were not statistically significant, implying homogeneous parameter estimates for those attributes in the sample population. The constant parameter representing the no-buy options (alternative specific constant terms) was positive and significant ($p < 0.01$) indicating a positive preference for this option. The heterogeneity in mean parameter estimates was statistically significant for the interaction term between vaccine cost and Bukedea district dummy variable at $p < 0.01$. This shows that the differences in marginal utilities for the vaccine cost attribute may be, in part explained by the farmer location effects. This is presented in **Table 6** which shows the differences in the random parameter coefficients across the two districts. The coefficients for vaccine viability detector was positive, whereas that for cost of vaccine and vaccine administration cost had a negative sign and were all significantly higher in Masaka compared to Bukedea district.

TABLE 6 | Coefficients of mixed logit random parameters, by district.

Attribute	District		Mean difference
	Bukedea	Masaka	
Vaccine viability detector	0.511 (0.015)[a]	0.727 (0.015)	−0.216***
Cost of vaccine	−0.844 (0.001)	−1.098 (0.002)	0.254***
Vaccine administration cost	−0.118 (0.000)	−0.235 (0.001)	0.117***

[a]Standard error in parenthesis.
****Denotes p-values at 1%.*

TABLE 7 | Vaccine attribute implicit prices (willingness to pay values) in United States dollars (US$) and Uganda shillings (UGX).

Attribute	US$	UGX	Standard error
Vaccine viability detector	0.495***	1,782	0.189
Price premium	1.173***	4,223	0.429
Low vaccination frequency (once)	−0.105	−378	0.084
Medium vaccination frequency (twice)	−0.077	−277	0.065
Weight gain	−0.094	−3,388	0.923

**** and ** denote significant variables at 1 and 5%, respectively.*

Willingness to Pay for *T. solium* Cysticercosis Vaccine

Estimates of the implicit prices of the vaccine attributes are presented in **Table 7**. The results show two key attributes that were highly valued by farmers: a high premium price for vaccinated pigs and inclusion of a vaccine viability detector. Farmers were willing to pay US$ 1.2 more for the vaccine if it would result in at least 1% market price top up as premium payment for a vaccinated pig. They were also willing to pay US$ 0.5 more if the vaccine comes with a viability detector. This did not differ between Masaka and Bukedea.

We used individual parameter estimates to assess the willingness to pay (WTP) for combined preferred vaccine attributes which includes a vaccine viability detector, a price premium due to vaccination and low vaccination administration costs. This was estimated at US$ 2.31(±0.39) for the overall sample. The WTP estimate was statistically different between Masaka and Bukedea farmers at $p < 0.01$. For Masaka the WTP was US$ 2.37 (±0.41) while in Bukedea it was US$ 2.24 (±0.36).

Table 8 shows the proportion of pig farmers choosing profiles depicting various vaccine options. The base scenario of the attributes is presented in vaccine option 1. This is the scenario that was used to describe the base scenario with an assumption of a price premium from the market for vaccinated pigs. Only 15 % of the surveyed farmers selected that option. The improvement in attributes of the vaccine presented in options 2 and 3 (**Table 8**) resulted in choice by a higher proportion of farmers. For instance, vaccine option 2 with lower administration cost (US$ 0.69), and a 50% price premium was selected by 37% of the farmers. Vaccine option 3 with 50% price premium, inclusion of a vaccine viability detector and a 10% increase in pig live-weight was selected by 49% of the farmers. The results show that under baseline scenario—only few farmers would be willing to take up

TABLE 8 | *T. solium* vaccine attribute options selected by a high proportion of pig farmers.

Attributes	Vaccine options		
	Option 1	Option 2	Option 3
Cost of the vaccine (US$)	5.00	2.92	2.92
Vaccine administration cost per pig (US$)	1.67	0.69	1.67
Price premium (% of market price)	15%	50%	50%
Vaccination frequency to attain immunity	Twice	Once	Once
Carcass weight gain (%)	5%	5%	10%
Vaccine viability detector	None	None	Yes
% of farmers choosing the vaccine option	14.9	37.4	48.9

TABLE 9 | Conditional logit estimates for *T. solium* cysticercosis vaccinated pigs.

Parameter	Coefficient	Standard error
Purchase price of pig in USD	0.040**	0.0177
Purchase price—squared	−0.000	0.000
Percent of premium top up price due to vaccination	1.847	1.384
Improved % pig weight gain	4.578**	1.787
Proof of vaccination—farmer's word	−0.194	0.218
Proof of vaccination government veterinarian certification	−0.255	0.373
Proof of vaccination private veterinarian certification	−0.079	0.210
Log likelihood function	−349.469	
Pseudo-R^2	0.1154	
Number of observations	1,056	

[a] *Base scenario for proof of vaccination—vaccinated pigs are ear tagged.*
***Denotes significant variables at 5%.*

the vaccine. Farmers are interested to pay for the vaccine if they are assured of a price premium and have confidence in the quality of the vaccine, through a viability detector.

Traders Preferences for *T. solium* Cysticercosis Vaccinated Pigs

The results of the conditional logit model estimation for *T. solium* vaccinated pigs is presented in **Table 9**. The results show traders preference for improved carcass weight of pigs ($p < 0.01$). Most of the other variables were not statistically significant, though had the expected coefficient signs.

DISCUSSION

Vaccine quality assurance is an important attribute highlighted by the farmers through their high preference for a vaccine with a viability indicator. This depicts a "lemons market" where consumers believe that products in the market are of low quality and will have a low willingness to pay for the product (34). This is usually pronounced when the quality assurance systems are weak, as is the case in Uganda. Pig farmers in Uganda have reported poor performance of products such as drugs and dewormers, which is due to the use of adulterated products, poor handling and misuse (35). Lack of transparency in pig trade, coupled with information asymmetry has been reported at the market level. Therefore, incorporating quality tracers would be of interest to the value chain actors, especially farmers for quality assurance. A similar scenario is reported by a World Bank study on pesticides in Uganda. The World Bank study found that one third of pesticides in the market were sub-standard. However, farmers believed that 40% of the pesticides were sub-standard and this substantially reduced their willingness to pay for pesticides (36). Other studies such as Wane et al. (37), Campbell et al. (38) and Ilukor and Birner (39) confirm the strong linkage between quality of veterinary products and services, and willingness to pay.

The results show preference for attributes associated with low administration cost of the vaccine, as well as cost of the vaccine itself. This confirms the high propensity by farmers to hold onto money as they have high time preference for money. Efforts to reduce transaction costs associated with administration of vaccines through communal vaccination campaigns have been successful in various livestock species. Such efforts can be replicated in this case with careful consideration of control for disease transmission due to mass handling of pigs from different households. The technical feature of the vaccine, requiring more than one vaccination for the pigs to attain immunity contributes to increased expense on the vaccine and the transactions cost associated with its administration. Ideally, one vaccine dose should provide lifetime protection for pigs, since in many production systems the life of a slaughter pig is about 12 months. According to Pedersen et al. (40) this might be possible by using delayed- or pulse-release vaccine formulations or by using live recombinant vaccine vectors.

In this study, pig farmers were willing to pay US$ 2.31(±0.39) for the vaccine with preferred attributes including low administration cost, quality assurance through a vaccine viability detector and premium payment for pigs due to vaccination. This is much higher than what they regularly spend to deworm their pigs—about US$ 1. Paying for a dewormer in combination with the vaccine may be unaffordable for most farmers in Uganda. In countries like Cameroon, pig owners indicated willingness to pay for the TSOL18 vaccine in combination with oxfendazole if the price is affordable (20). Studies such as Geerts (41) report that farmers were not prepared to pay for the vaccine even in areas hyperendemic with *T. solium* taeniasis-cysticercosis. The incentive to invest in the *T. solium* cysticercosis vaccine would be there if quality assurance systems are reliable and the markets provide premium price for vaccinated pigs, an attribute that was highly valued by pig farmers in this study. However, the pig trader results show that markets place more emphasis on carcass weight of the pig. The high carcass weight can be achieved with application of the oxfendazole dewormer to reduce worm burden.

In terms of sustainability of the *T. solium* cysticercosis vaccination efforts, an important consideration raised by Geerts (41) is consideration of who should pay for the vaccine—the pig farmer or the government? The answer to this question depends on whether the vaccine is considered a public good from which the community benefits or a private good from which the farmer benefits. In the case of *T. solium* cystercosis, both benefits. However, the farmers benefit only if they get premium prices, and it is important to note that pig farmers may not be willing to spend more than what they currently do for regular deworming. Results from this study show that the preferred vaccine and oxfendazole product would cost more than double regular deworming, making it unaffordable for farmers. Besides, pig vaccination left to farmers discretion is unlikely to reduce the infection pressure. The World Health Organization (1) considers the "best-bet" option for rapid reduction of infection pressure as a combined approach utilizing the treatment of human taeniasis cases through mass drug administration or selective chemotherapy combined with the vaccination (TSOL18) and treatment of pigs using oxfendazole. This should be supplemented by supporting measures such as health education and measures requiring fundamental social changes including improved meat inspection, improved pig husbandry practices and improved sanitation.

The results indicated that pig traders are aware of the importance of vaccinating pigs and the importance of safeguarding consumers health and safety. However, if there are no incentives mainly through improvements in pig carcass weight, they are not willing to pay a price premium when buying vaccinated pigs. In addition, the traders would not rely on farmers word as proof of vaccination. Considering that smallholders farmers are generally the main pig suppliers to traders (42), there is a need to find alternative ways to increase collaboration and trust between value chain actors and implement a reliable certification system.

CONCLUSION

The study analyzed the potential demand for the *T. solium* cysticercosis vaccine package by the Ugandan pig farmers and their preferences for its technical and administrative attributes. From the analysis, unless the pig market systems can pay a premium price for vaccinated pigs, and quality assurance systems guarantee quality of the vaccine, uptake of the package of TSOL18 vaccine and oxfendazole by farmers through market mechanisms may be unsuccessful. Yet, the current pig marketing system does not reward food safety, focus is placed on carcass weight. An alternative option would be for the package of TSOL18 vaccine and oxfendazole to be disseminated through a mix of public and private sector investments as recommended by Thomas et al. (43). The benefits to the community of *T. solium* cysticercosis vaccinated pigs are the decline and eventual disappearance of *T. solium* tapeworm carriers and, in the long term, neurocysticercosis (41). This is sufficient justification for a government to invest in consumer awareness and vaccination campaign against *T. solium* cysticercosis. The findings have implications for livestock diseases of public health significance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Research and Ethics Committee of the College of Veterinary Medicine, Animal Resources and Biosecurity–approval reference VAB/REC/15/127. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AC and SA conceived the study. DG, MD, NM, and EO developed the methodologies and tools. PL collected the field data under the supervision of MD and EO. NM and EO conducted the analysis. All authors listed have made a substantial contribution to the work and have approved this submission for publication.

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Community-Based Livestock Breeding: Coordinated Action or Relational Process?

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Over the past decade, community-based breeding programs (CBBPs) have been promoted as a viable approach to improving smallholder livelihoods through a systematic livestock breeding. CBBPs aim to initiate systematic breeding at the community level, including an organized animal identification and recording of performance and pedigree data. To ensure the breeding programs' continuity, building capacities, and ownership among participants are essential to the approach. This study's purpose was to understand how CBBPs have evolved in specific institutional settings and which dynamics occur in the course of implementation. We addressed these questions in reflective conversations with six coordinators of a diverse sample of CBBPs: goats (Malawi, Uganda, and Mexico), sheep (Ethiopia), alpaca (Peru), and cattle (Burkina Faso). The interviews and analysis were guided by categories of the multi-level perspective. The respondents considered lack of funding and weak institutionalization as the main constraints on the CBBPs. While the idea of participation and localized ownership was at the center of the programs, linear paradigms of knowledge transfer prevailed. In all cases, the impulse to start a CBBP came from individual researchers, who relied on intermediaries, such as extension agents, for implementation. Personal relations and trust were seen as both a factor in the success and a positive outcome of CBBPs. We conclude that these findings have different implications depending on how rural development is conceptualized: proponents of the innovation systems perspective would call for stakeholders to further align their interests and coordinate their actions. Proponents of process-relational concepts, in contrast, would not consider the CBBP a product but a starting-point for initiators and participants to continuously discover new ways of collaboration and engagement.

Keywords: community-based breeding, livestock breeding, small-holder agriculture, multi-level perspective, breeding program

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INTRODUCTION

Community-based breeding programs (CBBP) have been promoted as a strategy for smallholder farmers to improve livestock breeds. Mueller et al. (1) described these programs as "typically related to low-input systems with farmers within geographical boundaries having a common interest to work together for the improvement of their genetic resources." Typically, CBBPs define breeding objectives in a participatory process, which are then pursued in small-scale one or two-tier structures. The genetic resources are usually local so that CBBPs can also contribute to *in situ* conservation. Given the livestock keepers' role as the main agents in CBBPs, various authors have focused on their knowledge, needs, perceptions, and active participation (2–5). A wide range of literature also investigated the livestock keepers' selection criteria and breeding goals for different species and production systems (6–15). Using simulation models, another body of literature explored the potential genetic gains for diverse traits (16–20). Beyond these direct breeding-related questions, the effects of participating in a CBBP on economic benefits (e.g., marketing opportunities for breeding stock, meat, milk, and dairy products) to improve livelihoods were analyzed (21, 22). Opportunities for economic benefit largely depended on market access and integration, which were often poorly developed (23). Herold et al. (23) demonstrated, in their case study in Vietnam, how a pig breeding program could be strengthened via the integration of downstream processing and marketing stages.

As ultimate decision-makers, livestock keepers are usually considered the "owners of the breeding programs" in CBBPs. However, most initiatives also integrate different actors like extension services and research. Indeed, enabling policies, legal and institutional frameworks, and funding are seen as critical prerequisites to ensure the continuity of breeding programs (24–27). FAO (28) recognized in its Second *Report on the State of the World's Animal Genetic Resources for Food and Agriculture (SoW2)* that a diverse group of stakeholders is linked to breeding programs, suggesting the following categories: governments, breeders' associations or cooperatives, national or external commercial companies, NGOs or livestock keepers organized at the community level. Based on the report, Leroy et al. (29) concluded that development interventions should promote coordination among livestock keepers by creating and empowering cooperatives, associations, or community-based institutions. While CBBPs commonly start as small initiatives, the wish to scale out (including more farmers/communities in the region) and up (including additional actors, such as policymakers) is implicitly present. Kaumbata et al. (30) described the difficulties of CBBP scaling and concluded that it needs to be part of a breeding program's initial planning stage.

The question of how to initiate and facilitate change in agricultural practices is not specific to breeding, but a general concern in research and intervention to improve smallholder farmers' livelihoods. CBBPs and the strategies to mainstream the breeding approach in rural communities can be seen as part of this endeavor and emerged from participatory approaches to rural development (31). By including multiple stakeholders along the value chain and in the institutional environment, the approach also resonates with the more recent concepts of Agricultural Innovation Systems (32). The innovation systems perspective conceptualizes change in agricultural practice as emerging from the actors' interplay, strongly affected by the institutional environment (33). While particular aspects of CBBPs have been thoroughly analyzed (e.g., technical, financial), there has been no detailed discussion of the institutional and social dynamics that affect CBBP initiation, facilitation, and ownership transition. Therefore, this study aimed to understand how CBBPs evolve in specific institutional settings and which dynamics occur at the project level.

However, the perspective of innovation systems does not theorize processes at the group or personal level—including the values and meanings actors relate to their practice [e.g., (34, 35)]. Higher-level trends (e.g., climate or political dynamics) that can affect livestock breeding interventions are not easily integrated. To fully capture the evolution of different CBBPs, we, therefore, refer to El Bilali et al. (36) and their adaptation of the multi-level perspective (37, 38). We conceptualize CBBPs as *niches*, spaces where a novel approach to livestock breeding is introduced. This niche confronts or aligns with the *regime*, i.e., the current practices, rules, and institutions (e.g., agricultural policies, research in animal breeding, markets for livestock products). The *landscape* includes pressures and opportunities that cannot be influenced by niche actors but impact how the niche can develop. Examples of landscape trends are climate change, demographic change, and trade dynamics. The theoretical considerations were translated into an analytical framework specifying the categories and variables included in the data collection and analysis (**Figure 1**).

MATERIALS AND METHODS

Research Instrument and Data Collection

The case studies were selected to cover a wide range of production systems and species (small ruminants, cattle, and alpaca). We included a mixed crop-livestock but also sole livestock

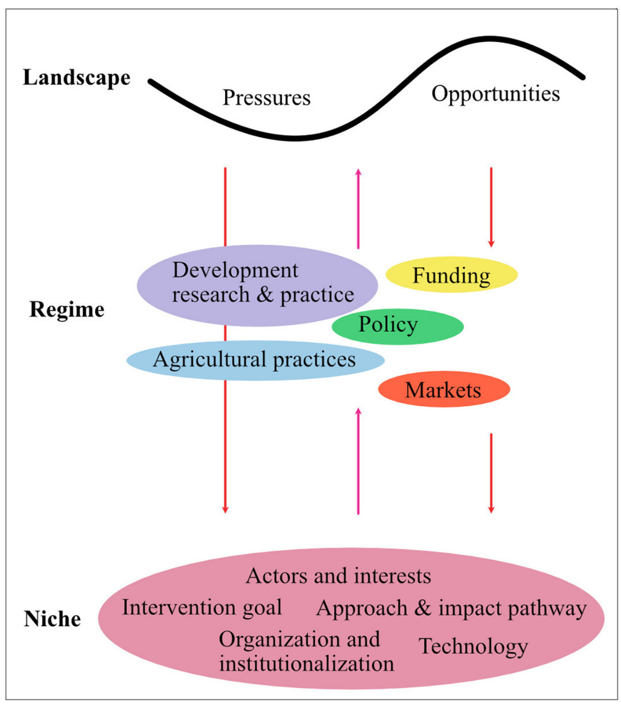

FIGURE 1 | Analytical framework: CBBPs as niches linked to the regimes and landscape [Adapted from: El Bilali et al. (36)].

TABLE 1 | Details of selected community-based breeding programs.

Country	Species	Implementation period	Funding sources	Involved actors	Interventions
Malawi	Goats	2014–ongoing	USAID	• National University • Extension service • Farmers • International partners	• Male selection • Formation of cooperatives • Market linkages (butchers)
Uganda	Goats	2014–ongoing	USAID	• National research organization • Farmers • International partners	• Male selection • Formation of cooperatives • Market linkages • Animal health
Ethiopia	Sheep	2009–ongoing	Multiple	• National and regional research organizations • National University • International partners • Farmers	• Male selection • Formation of cooperatives • Market linkages • Animal health • Animal nutrition • Certification of breeding animals
Burkina Faso	Cattle	2017–ongoing	ADA	• National research organization • National universities • Extension service • Farmers • International partners	• Male selection • Formation of cooperatives • Animal health
Peru	Alpaca	2010–2020	VLIR	• National University • Farmers • International partner	• Male selection • Rangeland management
Mexico	Goats	2007–2015	Multiple	• National research organization • Farmers • International partners	• Male selection • Formation of cooperatives • Animal nutrition • Animal health

USAID, United States Agency for International Development; ADA, Austrian Development Agency; VLIR, Flemish Inter-University Council.

TABLE 2 | Code categories and specification.

Category	Codes
Landscape	• Landscape drivers • Landscape constraints
Regime	• Policies • Markets • Research and education paradigms • Default breeding paradigms • Funding
Niche	• Project goal and impact pathway • Organization & institutionalization • Actors & interests • Technology • Character of activities
General reflection	• Male selection • Formation of cooperatives • Animal health

production systems. The projects varied in initial size (number of participating livestock keepers), but were also at different implementation stages: the oldest project was initiated in 2009, whereas the most recent one was started in 2017. **Table 1** shows the details of the included breeding programs.

Since CBBPs are a niche also in animal breeding sciences, all coordinators of the considered CBBPs were personally known to the authors. We define "coordinator" as the person responsible for the design and for the implementation of the CBBP on the ground. The first author contacted the coordinators of the CBBPs, inviting them to participate in the study as expert respondents. All respondents were permanently employed researchers of universities or research organizations. An additional interview was carried out with a senior scientist who has an experience with implementing community-based breeding programs in different regions and was thus able to contribute more general insights.

The interviews, conducted via zoom or Skype in July and August 2020, followed a guide based on the analytical framework (**Figure 1**). The interview strategy was to facilitate an open conversation that creates a rich picture of the respondents' experiences with CBBPs.

All interviews were held in English and respondents gave free prior consent for the interviews to be recorded and analyzed.

Data Analysis

The first author transcribed the interviews. For qualitative data analysis, we used a deductive coding strategy (**Table 2**) based on the analytical framework to structure the results. Atlas.ti Cloud was used for coding, which allowed all team members to work in parallel on the documents.

RESULTS

We report the results along the analytical framework, starting with the higher-level trends at the landscape level, then narrowing the focus on the regime and niche.

Landscape Level: Funding and Population Dynamics

The respondents did not explicitly refer to the higher-level drivers and constraints in their reflection on their respective CBBP programs' history. They considered funding as the primary external variable they could not influence, which directly impacted their efforts' effectiveness and permanence.

"If you don't have money, you don't have a project. If you don't have a project, you cannot work on anything." (Respondent 2, Mexico)

While all CBBPs had started as externally funded projects, the respondents agreed that a shift toward continued national support would be necessary for community-based breeding to be successful. CBBPs cannot be considered a one-time intervention:

"When people say "Yes, let's do CBBP," I say, do you have plans to invest over a long period into this program? If you don't want to do that, and you see it as a short term—forget it. It is not worth starting, it is something where you waste your money, you need long-term funding, and you need the support from the national system to do for a long time." (Respondent 3, Ethiopia)

In addition to funding, the role of the policies aimed at conserving and improving local animal genetic resources was also emphasized. Such policies provide the legal framework for the implementation of the breeding programs.

"And this has to be backed up by policies. A national policy saying the improvement and management of the national animal genetic resources of the country." (Respondent 7, Bolivia)

Beyond the political landscape, the respondents also acknowledged that broader societal dynamics could drive or constrain a change of breeding practices. In the case of Bolivia, for example, the aging rural population, outmigration of the young labor force, and small farming units were considered as factors that limited continuous breeding efforts. However, in turn, low productivity and vulnerable livelihood systems may also inspire efforts to introduce alternative livestock breeding approaches.

Regime: Transfer of Technology and Participatory Approaches

Current livestock breeding practices in the analyzed cases involved different species but were commonly characterized by low levels of systematic breeding, which includes animal identification and recording of performance and pedigree. In free grazing arrangements, random mating was the default practice, and particularly in meat-oriented systems, negative selection due to selling of the best young males was a significant challenge. This practice resulted in a shortage of locally available breeding males. Also, the prolonged use and the rare exchange of breeding males led to the perceived high inbreeding levels. Where deliberate breeding efforts were made, criteria were not consistently applied nor the records kept. Against this background, according to the respondents, the general perception was that performance improvement would require the introduction of exotic breeds and crossbreeding:

"When they say that we bring in a goat project, they expect something to be introduced to their system. And that something should not be local, but exotic. So, that was a major drawback to the CBBP." (Respondent 4, Malawi)

However, the lack of adaptation of exotic breeds, loss of breed diversity, and lack of infrastructure and funding caused the systematic crossbreeding schemes to be unsuccessful in most cases. Consequently, it became a general assumption in development programs that systematic breeding in low-input systems with smallholders was not a promising strategy.

This tension was also reflected in the way the respondents conceptualized their own efforts in facilitating a community-based breeding. Their approaches reflected different paradigms, often simultaneously in a single project. Fundamentally, all analyzed CBBP initiatives were part of the donor-driven, project-based development logic. Most respondents also referred to institutions from "outside" (universities from the global North, CGIAR-centers) as essential in the start-up phase of the CBBPs. When reflecting on the specific projects, the idea of transferring the approach of breeding through CBBPs from the researcher through the extension to livestock keeper emerged frequently. Also, the question of whether a CBBP is a social intervention or needs to be run by a breeding scientist arose:

"For example, in Mexico, we had a colleague who is technically very solid, but he says that a CBBP is just talking, just sociology, this is not animal breeding." (Respondent 9, Mexico)

At the same time, all respondents considered their CBBP as highly participatory and suggested that their role was mainly on guiding the participants. Even in this participatory narrative, however, the livestock keepers' ownership in the projects seemed to be limited. In almost all the cases, the CBBPs were wholly dependent on the initiators for keeping the momentum, and participants often expected the projects to "bring" something immediately valuable to them.

Although the policy level was considered important by the respondents, the CBBPs were not explicitly constrained or strengthened by the national livestock policies. The projects made an effort to legitimize the approach toward the policymakers, who were generally supportive mainly on where funding was brought in, and successes were visible and could support their agenda. In most projects, the respective ministries were directly involved—in Uganda, the implementing body was a parastatal institution directly under the ministry, and the other projects consulted with ministry representatives in the site selection and gave progress reports. It is only in Peru where no formal exchange with the policy level was established.

According to the respondents, an aspect that had been frequently overlooked in breeding-related projects was the market linkages. For CBBPs to take lasting roots, securing market access for their products (meat, fiber, milk) and, in a further step, breeding animals are essential. CBBP initiatives can play a facilitating role in establishing market linkages.

> *"You have a breeding program, but it needs to be embedded in the wider context if you want to have this value chain transformation of the livestock sector. Because having the better animals alone, but you also need a market that will take these improved animals." (Respondent 3, Ethiopia)*

Niche: Projects to Improve Livelihoods Through Community-Based Breeding

The CBBP initiatives had the common long-term objective of improving the livestock keepers' livelihoods. In the medium term, the projects hoped to achieve improved livestock breeding practices and, consequently, higher productivity at the community level.

> *"You ask if you can live off the products of 30 llamas? Can I provide my livelihood? How much would I have to improve my llamas in order to make my living?" (Respondent 7, Bolivia)*

The assumed impact pathways followed a linear logic, proposing to scale-out CBBP practices through extension or NGO actors while simultaneously scaling-up the CBBP approach at the national and local policy levels. The central user outcome was to build the livestock keepers' capacities in systematic breeding for genetic improvement, and in some cases, supporting institutionalization. The marketing of animal products or breeding animals (livestock trade, dairy sector, butchers) was not typically included but considered relevant when looking back at the CBBP experiences. Policymakers at different levels, from national actors to local administrative units, were provided with evidence on the potential of CBBPs and explicitly addressed to mobilize further support for the initiatives.

In a typical CBBP arrangement, researchers calculated a ranking of the potential breeding males based on the data collected by the enumerators, who were often extension agents. The collection and management of data was a challenge in all projects, and in Ethiopia, the use of tablets was a significant improvement. The ranking was provided to the livestock keepers' selection committees, who made the final selection based on the ranking and their own preferences. The respondents considered this final step as the central aspect of signaling CBBP ownership to the livestock keepers.

Except for Mexico, all projects focused initially on the implementation of breeding programs. In Mexico, the CBBP emerged from a project on nutrition and animal health interventions. The other projects later included accompanying activities and outcomes (e.g., rangeland management plans, vaccination, and animal health checks) to bridge the time lag between breeding efforts and visible results.

The impulse to start a CBBP came in all cases from individuals at universities or research organizations who had personal ties to a specific region. Except for Peru, these initiatives could not build on existing associations or cooperatives, but all respondents saw such institutions as necessary to start a CBBP and ensure its continuity effectively. The respondents further stressed the importance of institutionalization:

> *"What we underestimated was the institutional set-up, which is really needed. How much institutional set up you actually need and how well this has to be set up." (Respondent 3, Ethiopia)*

In some cases, respondents found that livestock keepers were less interested in collaboration than expected, or livestock was not their focal activity. Where the projects facilitated setting up of cooperatives or associations, the collaboration with the project was not specified in formal agreements. In all cases, a crucial role was assigned to intermediaries, such as extension agents, who were counted on to link the research system (national and international universities and institutions) to the livestock keeping communities, record data, and monitor breeding implementation. In Peru, however, an extension system was not in place, and partly, the projects had no choice but to pay the extension agents—which may, in turn, might give rise to problems of continuity:

> *"They consider [the CBBP] their own. They are government employees, so you can ensure long-term sustainability. In other regions, when we sent them some money, this is how they paid the enumerators. This is not the right way to do." (Respondent 4, Ethiopia).*

Combining the CBBP project with the capacity building in higher education (involving MSc/PhD candidates, technical staff) was evaluated as a very positive outcome by the respondents. Some universities adapted their curricula as a result of their participation:

> *"And we have already got two courses. One is animal breeding and genetics at the undergraduate and a similar one applied animal breeding at the Masters level. We have integrated this and we got another course called "Farm animal genetic resource management" and part of the conservation methods, which is heavily related to goat breeding. The concept of community-based conservation has come on board. So, we are now using these as case studies." (Respondent 3, Malawi)*

Contingent upon the projects' capacities, scaling-out to neighboring communities and scaling-up through including additional actors were common strategies. Out-scaling did not always follow a planned process, but neighboring livestock keepers could get an idea of the success in informal contacts. Up-scaling proved to be difficult in some cases because organizations identified as potential partners did not have the necessary technical know-how and the required budget to get involved.

By bringing together actors along the value chain and the wider innovation system, the CBBPs resonated with the current approaches of multi-stakeholder platforms. Within the stakeholder groups, specific inspiring individuals had a pivotal importance in driving the CBBPs—be it at the research, policy, extension, or farm level. At the same time, the data show that agency in the initiatives was concentrated around the initiating researchers and practitioners—who described their involvement mainly using verbs like monitor, use, show, start, make, work, and move. Participants, on the other hand, were referred to mainly using passive forms, such as: were taught, were informed, were trained, and were requested. Accordingly, the respondents described success on the participants' side using attributes such as improved understanding, new abilities, or recognizing change.

Nevertheless, when reflecting on the key factors of success, several respondents strongly emphasized the importance of *being* with the livestock keepers, of relating in a trustful and committed way:

> *"And it was part of having a huge lunch over there with enchiladas, tacos and much good stuff for food and some music. It was kind of a party." (Respondent 9, Mexico)*

The dilemma of initiating a process that should be owned by someone else thus remained unsolved. Entrusting livestock keepers with more responsibility right from the beginning and giving them more decision-power was seen as one way to foster ownership:

> "*Start and let them lead more the program. Let that they organize, that they make some organizations, that could be among them in order to strengthen the alpaca breeding program.*" *(Respondent 1, Peru)*

Reflections: How to Make Community-Based Breeding a Success

When reflecting on further support that would have helped the CBBPs take firmer roots, the respondents mentioned a stronger and continuous backing at the national and local policy level. The role of intermediaries in facilitating the introduction of CBBPs was described as crucial where extension services were in place—the lack of such facilitation was, in turn, seen as a major constraint. This constraint was related to the institutionalization and social momentum necessary to establish or strengthen breeding associations who would own the CBBP after the end of a project. Respondents saw these institutions as essential to fostering the trust necessary for exchanging animals. At the implementation level, the respondents highlighted that appropriate tools (e.g., offline-ready apps) could make a significant difference in the daily work of a CBBP.

Reflecting on the CBBP process, the respondents described several tensions and ambiguities that a project has to navigate in the different phases from inception to hand-over. First, all respondents saw a need to better understand the values, knowledge, and livelihood strategies of the potential CBBP participants before introducing the concept. To gain such understanding and to build trust and a good working relationship, the respondents considered it essential to explicitly invest in continuous communication, transparency, and timely feedback. However, winning trust takes time and requires consistent action and tangible results:

> *"Farmers just trust you when they see what you are saying is right. So I think, in areas where we have been, we were quite transparent and we tried to support them and they see something really happening on the ground." (Respondent 3, Ethiopia)*

At the same time, CBBPs require capacities that participants may need to develop. All experts agreed that capacity development, not only for the livestock keepers but also for the technical staff, was an essential element of their projects. Second, better tools to register animals, record herd development, and certify breeding animals would ease the implementation. However, providing these services may jeopardize participant ownership and commitment. Third, CBBPs are long-term investments that require continuity, particularly at the facilitation and management level. This, however, does not fit well with the project-logic in research for development. Finally, institutionalizing CBBPs at a community level and beyond proved to be essential. Such institutions, however, cannot be imposed and need to balance the structural requirements of a CBBP with the freedom for participants to take ownership and initiative beyond the project.

DISCUSSION

CBBPs Are an Established Niche

Our results support the current perception in the literature: CBBPs are an established niche—approach to livestock breeding in smallholder agriculture, with the potential to improve livelihoods (21, 22). The number of publications related to community-based breeding has increased over the past several years [e.g., (27, 28)]. The universities which partnered in the studied cases are examples of how the approach is transmitted rather quickly into specific courses and can later be formally integrated into the entire curricula. This integration adds to the legitimacy of CBBPs, and future graduates may accept and apply the approach more readily. Our results also suggest that CBBPs have not reached a mainstream practice stage, embedded in the rules and institutions at a regime level. If we consider community-based breeding as a viable pathway to improve livelihoods, the question arises of how a more substantial change of livestock management and breeding could come about. We discuss this question from two different perspectives: coordinated action in an innovation system and self-organization in flexible social relations.

Coordinated Action Toward Community-Based Breeding

With their CBBPS, the respondents met an institutional environment that lacked organization or favored the common transfer-of-technology approaches. As a response, all respondents called for a better organization and institutionalization of livestock breeding, including CBBP mechanisms, in their respective project areas. According to Picot et al. (39), the institutional term ”organization“ covers a whole system of institutions like markets, agreements between business partners, but also the legal framework, and public organizations. Indeed, Herold et al. (23) proposed that ”organization is an important factor in animal breeding.“ The authors distinguish between the process-oriented, instrumental, and institutional definition of ”organization.“ The main focus in the projects we investigated for this study was at the level of “process-orientation.” Data recording and performance testing of selection candidates, an area for which much time and effort was spent, was a typical example. Roles and responsibilities for the different steps were coordinated and shared between livestock keepers, field staff, and researchers. The ”instrumental“ dimension refers to a breeding organization’s internal structure, in our case, livestock keepers’ cooperatives or associations. This structure encompasses the rules and decision-making mechanisms of these organizations. Although the respondents repeatedly emphasized the importance of the cooperatives, they also indicated that knowledge about facilitating institutional change was limited among the initiators of the CBBPs. In general, the literature suggests that livestock keepers can benefit from being a cooperative member, but membership can come with problems and pitfalls. In the European context, Schmitt and Momm (40) recommended a two-level organizational structure for breeding associations with a general assembly for all members and a board consisting of elected representatives. To our knowledge, this issue has not been addressed in the context of smallholder farming, thus being an area of research that should be given more attention in the future. Several authors (1, 16, 19, 20) discussed different breeding strategies such as central vs. dispersed nucleus or group breeding systems, but their analysis does not address the question of how these different approaches should be reflected in the structure of breeding organizations.

Beyond the organization of breeding, a further point of discussion both among the respondents and in the literature is the vertical integration of breeding associations in the value chain. This could create opportunities for members by adding value to primary products. Herold et al. (41) illustrated how such integration could be achieved in a Vietnam pig breeding program. In our study, respondents also suggested that a division of labor between specialized breeders and regular livestock keepers as their customers could be a future scenario.

Finally, the question of funding and continuity emerged as the primary concern of respondents. All presented cases had started as externally funded projects but without a clear vision of how the breeding programs should be financed in the long-run. The initiators seemed to have assumed that the national or regional government would take up this role. However, after 10 years of continuous effort, the sheep breeding program in Ethiopia was still partly dependent on external funding, even though there is a strong political interest from the national government. CBBPs are included in the livestock development plan as the breeding strategy of choice. Lobo (25) and Gowane et al. (26) stressed the importance of public funding and the challenges caused by an insufficient and fluctuating support. Accordingly, they proposed to develop breeding programs that are self-sustainable and profitable. Where a private sector is not well-developed or even absent, this may be very ambitious.

In conclusion, coordinated action and alignment of interests are imperative to promote CBBPs from the innovation systems perspective. From the outset of community-based breeding programs, the understanding of the stakeholder network and institutional environment needs to be a primary focus—as well as the facilitation of institutional learning and creation of ownership.

Community-Based Breeding as a Relational Process

What if it is impossible to meaningfully describe and replicate an institutional set-up that will allow the scaling of CBBPs? What if there is no continuity in the collective action without the initiating researcher? These questions, resonating with the ambiguities and tensions we identified in the respondents’ reflections, arose during this study’s write-up.

From an innovation systems perspective, we discussed coordinated action and alignment of interests as imperative. In the data, however, there is little evidence of CBBPs being a stable systemic arrangement, even in the most structurally established case of Ethiopia. Instead, the analyzed CBBPs seem to be constantly evolving, and discontinuation is not an unlikely scenario. The main commonality we found across the cases was the impulse of an “intentional and purposeful activity” (42)—driven by researchers who shared the belief in improving livelihoods locally, in a fair and participatory manner. At the same time, the different CBBPs remained fragmented, as unequal power relations prevailed with researchers and extension officers being in the position of the key mediators. We also have to assume that the communities and breeding associations involved were not necessarily egalitarian, but highly differentiated—an aspect that did not come up at all in the respondents’ reflections. Most tangible were the fragmentations when respondents described their efforts to reconcile project logic and collective action, steering and letting go of their program, and being an expert on breeding but trying not to impose this knowledge on the participants.

This confusion cleared when the respondents reflected on what worked well: the integration of community-based breeding in their own teaching practice at the University, the time they spent celebrating in the communities, the trust that developed between them and the livestock keepers, and the personal satisfaction derived from seeing community-based breeding in action. This finding is consistent with Umans and Arce (43), who suggested that change is more likely to be the outcome of engaging with the reality than of planning and design. Indeed, it has been disputed whether collective action, institutions, and social norms can be planned at all (44).

Accordingly, we could argue that the absence of institutions allowed the initiators to create CBBP interactions in a way they value. Instead of focusing on institutions that enable or constrain, and seeing a CBBP as an end-product separate from the researcher, this perspective would consider the CBBP as an ongoing process in which relations between social actors are made, transformed, and abandoned (45). Process-relational theories propose that the order in institutions is contingent, not continuous—the only social reality would be the series of events and relations that temporarily create something called CBBP. Consequently, the CBBP would be something very diverse for the plurality of the people involved.

The process-relational perspective does not resonate well with our wish for clear causalities and stability—it does, however, provide openings for new conceptualizations of how CBBPs could be seen and promoted: as a practice that the initiators coherently integrate into their work and lives (42). When community-based breeding becomes part of their own continuous engagement as members of the community, social change may be more likely to emerge from a sense of responsibility and accountability.

CONCLUSION

Community-based breeding programs have been promoted as a viable approach to systematic livestock breeding in low-input smallholder farming contexts. The purpose of this study was to understand how CBBPs evolve in specific institutional settings, and which dynamics occur at the project level. The respondents considered funding as the primary higher-level variable, which they could not influence. While the idea of participation and localized ownership was at the center of CBBPs, the programs had to follow a typical project logic as researchers remained the main mediators, and linear paradigms of knowledge transfer prevailed. Most CBBPs sought to lobby for policy support, and some included efforts of market integration—an aspect that had been frequently overlooked in the past. In all cases, the impulse to start a CBBP came from individual researchers, who relied on intermediaries, such as extension agents, to implement the program. Relating in a trustful and committed way was seen as a critical outcome and success factor, while further institutionalization was called for. We conclude that CBBPs are an established niche concept—to support social change toward systematic breeding in smallholder contexts, two different perspectives may be helpful: from an innovation systems perspective, coordinated action and alignment of interests would be necessary. From the perspective of process-relational concepts, CBBPs could become a part of the researchers' daily practice and their continuous engagement with a community.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MW and LP developed the concept, analyzed the data, and prepared the first draft of the manuscript. GG and JS commented on the manuscript. All authors read and approved the final draft.

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Strategies to Upgrade Animal Health Delivery in Village Poultry Systems: Perspectives of Stakeholders From Northern Ghana and Central Zones in Tanzania

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Village chicken production holds much potential for the alleviation of malnutrition and poverty in rural communities in Africa. Owing to their subsistence nature, however, such systems are rife with infectious poultry diseases such as Newcastle disease (ND). Strategies common for the management of ND and other poultry diseases in intensive production systems, including vaccination and biosecurity measures, have seen limited success in the village production systems. New approaches are needed that can successfully deliver animal health inputs and services for the effective management of poultry health challenges in low-input systems. Our study utilized focus group discussions with men and women farmers as well as other poultry value chain actors such as input suppliers, live bird traders and processed poultry meat retailers, to investigate potential options for delivery of animal health care to village poultry systems in northern Ghana and central Tanzania. ND was commonly reported as a major disease constraint in the study sites of the two countries, with resulting fatalities particularly impactful on men and women producers and on traders. We therefore also conducted interviews that focused specifically on the gender component of village chicken production. The key health related challenges prioritized by women and men participants included limited access to, and poor quality of, vaccines and veterinary drugs, a shortage of veterinary officers, and insufficient knowledge and training of farmers on flock management practices. Women, more than men, emphasized the difficulties of accessing poultry health services. Our assessments suggest that for poultry health care delivery in the studied communities to be effective, there is need to improve the supply of good quality drugs and vaccines in rural areas, respond to the needs of both men and women, and recognize the different incentives for farmers, traders and other value chain actors. Community-based approaches and increased use of ICT technology such as mobile phones have much to offer in this regard.

Keywords: poultry, value chain, newcastle disease, veterinary service, smallholder, gender, focus group discussion, qualitative analysis

INTRODUCTION

Small-scale chicken production holds much potential for the alleviation of malnutrition and poverty in rural communities across Africa (1). However, low productivity is a major feature of village poultry production in the region, limiting capacity of smallholder poultry to deliver on its potential for addressing poverty and food security (2). Infectious poultry diseases are a key factor driving low productivity of village poultry production systems (3). In this respect, the overall inability of animal health care systems to effectively reach women farmers—observed in Tanzania and Ghana (4, 5)—makes the small-scale poultry sector, generally in the hands of women, even more vulnerable to diseases.

Although data are limited, high mortality rates in village flocks are primarily attributed to Newcastle disease (ND). ND is a highly infectious viral disease among domestic and wild birds. Virulent strains can cause up to 100% mortality among affected flocks resulting in major economic losses each year (6–8). In addition to ND, coccidiosis, fowl pox, infectious bursal disease, and less commonly avian influenza cause high morbidity and mortality in village flocks in Africa (9–11). Chickens raised in extensive production systems with minimal biosecurity measures and restricted access to veterinary inputs, including pharmaceuticals, are at increased risk of these diseases (12–15).

Disease control is difficult to carry out under free-range conditions in resource-constrained areas and is therefore limited in practice (16). Good husbandry and biosecurity practices (e.g., regular clean animal pens, quarantine new birds, isolate sick birds from the flock) provide relatively inexpensive and effective prevention measures for infectious diseases. However, most village poultry producers have not had any training on poultry keeping and there is a critical need to increase knowledge and best practices of producers. Additionally, although not always readily available to smallholder producers, vaccination offers an effective approach to specific diseases. For example, when carried out appropriately, vaccination against ND in village poultry flocks has been shown to be an effective control strategy resulting in decreased mortality and consequently increased income, utilization of poultry products, and nutrient intake among households (3, 17, 18).

In many low-input poultry systems such as the village poultry production systems, considerably more effort is needed to bridge critical gaps in policy, co-ordination, quality assurance, packaging, administration, evaluation and monitoring, training, and gender-sensitivity to facilitate successful vaccine delivery (18, 19). Such an environment could hinder investments into vaccine supply on the part of public and private agencies, as well as vaccine uptake by smallholder producers. A recent study found that while chicken-owning smallholders households place value on, and benefit from, vaccines against ND, they face substantial other barriers to vaccination (20). Studies such as (21) have highlighted the importance of market-driven approaches to addressing non-technical constraints to vaccine availability while other studies have stressed the need to understand preferences of small-scale poultry farmers and to recognize that these preferences could differ for women and men (22, 23).

Conceptually, a successful system for the delivery of animal services to village poultry value chains, at least in the context of ND management will be one that adequately addresses issues of weak effectiveness, poor availability, and inequitable access to animal health inputs (e.g., vaccines and veterinary drugs). It should also account for concerns about user perceptions and experiences of the services. The poultry value chain refers to the range of activities involved in moving product (in this case live poultry and poultry products) from the village producer to the final consumer. To be sustainable, a technically efficient animal health system serving the poultry value chain must in addition provide the right mix of incentives to relevant value-chain actors, i.e., producers, private investors and other decision-makers that critically affect its success (19). In practice, ND control programs across Asia, Africa and Latin America that have been considered technically sound and sustainable included various elements of quality control in veterinary pharmaceuticals manufacturing, field level quality assurance, the involvement of men and women farmers in program monitoring and evaluation, and active collaboration with relevant government ministries (18).

In Tanzania, constraints to development of the poultry sector are reported to include poor quality of inputs particularly veterinary drugs and vaccines, inappropriate use of veterinary drugs and vaccines and limited access of farmers to quality veterinary and extension services (24). While a locally produced vaccine (called I-2) is available that is heat stable and can withstand high temperatures (37°C), making it suitable to an environment with limited cold chain capacities; it's use is not widely established and many poultry farmers raising village breeds of chicken rely on heat-labile vaccines. Heat-labile vaccines tend to lose potency or viability if stored under unrefrigerated conditions (2–8°C) for prolonged periods (25). Electrical power shortages, non-functional and obsolete storage equipment, and inadequate temperature monitoring and control during transportation are amongst the problems constraining cold-chain vaccine delivery in rural Tanzania (26). As in many developing countries, the cold chain is usually more reliably maintained going from manufacturers to importers and distributors but becomes less so from vaccine distributors to the end-users (27).

While vaccine development and approaches to animal health care delivery in Ghana and Tanzania may over the years have better incorporated market and social considerations in their design (21, 28, 29), vaccine use is still not widely adopted in the low-resource poultry systems of both countries (30). There remains considerable ineffectiveness in the management of diseases like ND, particularly amongst producers in rural areas. To help shed light on this constraint and to assess potential solutions, our study investigated three main research questions: (1) What are the key constraints to animal health care delivery to small-scale poultry producers in northern Ghana and central Tanzania, viewed from the perspectives of the value chain actors most affected (e.g., chicken farmers and veterinary input providers); (2) How do these constraints impact on producers and others in the value chain; and (3) how does ND impact women and men farmers and other value chain actors. The responses to these questions help answer a final question: (4) What key market, institutional and other interventions could enhance the effectiveness of animal health care delivery in Ghana and Tanzania to better benefit village poultry production systems in the two countries.

The study is part of a larger study focused on development of appropriate business models to enhance the distribution of new chicken lines with improved genetics for ND resistance in village poultry production in the two countries. Breeding for resistance to viral infections is considered a viable option for addressing the ever-present threat of infectious diseases in poultry systems in Africa, given the vast genetic potential of local African chicken ecotypes (10). This approach has gathered momentum in recent years and is the focus of an ongoing research-based intervention for village poultry production in Ghana and Tanzania (30). The chicken ecotypes developed through such breeding strategies are expected to confer significantly improved but only partial resistance to ND. As such, attention still needs be paid to ways of improving animal health management and the delivery of veterinary inputs and services as part of the value chain upgrading that will be needed to support enhanced village chicken production (30, 31).

MATERIALS AND METHODS

Value Chain Assessments

To address the research questions, we conducted assessments of the poultry value chains associated with village chicken production in selected sites in Ghana and Tanzania. Gender, participatory epidemiology, and value chain assessment frameworks were used to guide the poultry system assessments. The frameworks were operationalized through participatory appraisal methodology utilizing a value chain assessment toolkit developed under the CGIAR Research Program on Livestock (32). The toolkit provides a set of tools to analyze livestock value chains and identify, monitor, and evaluate interventions that improve value chain performance and gender inclusiveness. It has been applied widely, for instance in the Uganda pig value chains (33), in the Tanzania dairy value chain (34), and the Burundi dairy value chain (35). We applied participatory methods including pairwise ranking and value chain mapping, guided by semi-structured interview checklists adapted from the tools. Three tools from the value chain assessment toolkit were utilized.

The participatory epidemiology tool was used to identify poultry health constraints and priority diseases and their impact on poultry production systems. The value chain assessment tool was used to identify overall backyard poultry value chain constraints, map out the marketing channels for chicken, inputs and services, and document prices along the marketing channel. The gender tool was used to assess men and women's participation in the poultry value chain, identify gender-based challenges in accessing poultry inputs and markets, and identify challenges associated with poultry diseases.

Study Area

The study was conducted in Singida and Dodoma regions in Tanzania and in Upper East region and Northern region in Ghana. The 4 regions were identified based on location of production of local chicken ecotypes, high frequency of Newcastle disease occurrence and proximity to demand areas, specifically towns such as Tamale, Bolgatanga, Dodoma and Singida. The regions are locations with growing demand for indigenous breeds of chicken. Identification of the study regions was informed by desk review and site scoping studies conducted in 2019 to identify potential target groups and poultry systems for chicken lines with enhanced ND virus resistance. The selected regions are characterized by a high population of local chicken ecotypes and households raising poultry under backyard systems.

In each region, two districts were selected for the value chain assessments, one representing peri urban chicken production and the other, rural chicken production that is far from urban demand centers (30). Within each district, two second level administrative divisions were selected (Metropolitan, Municipal and District Assembly, or MMDA for Ghana and ward for Tanzania), yielding a total of eight sites per country as depicted in the spatial maps in **Figure 1** for Tanzania and **Figure 2** for Ghana, and in **Table 1**. Dodoma and Singida regions are in Central Tanzania and are among the regions with high indigenous chicken population. The number of households keeping chicken in Dodoma was 139,992 in 2006, raising about 1,825,867 chickens (36). In Singida, the number of households keeping chickens was estimated at 125,895 raising 1,658,178 chickens (*ibid*.). Livestock keeping is the second major economic activity in the regions, with chicken rearing being one of the most important activities. Dodoma region has a dry savanna type of climate, which is characterized by a long dry season lasting between late April to early December and a short single wet season from January to March (37). Singida region receives rainfall from mid-November till April or early May every year (31). Temperatures in both regions range between 15°C and 30°C depending on season and altitude.

Upper East Region and Northern Region throughout the study refer to administrative units in Ghana established in 1987 and bearing those names until early 2019. The Upper East and Northern regions of Ghana account for 46% of backyard chicken production, comprising indigenous chicken, guinea fowl and turkey (38). The Northern region has a chicken population of 1,744,799 and the Upper East region has a smaller population of 578,647; while the guinea fowl population is 1,414,649 in Northern region and 622,616 in Upper East region (*ibid.*). The two regions are in Northern Ghana and fall within the Northern Savanna ecological zone, with a vegetation largely comprising grasses, short woody trees, and shea and baobab trees. Daily temperatures are variable but characteristic of savanna zones, with an average daily temperature of 34°C. Some months, especially July to September are very humid. The Northern and Upper East regions are classified among the top three poorest regions in Ghana (39).

Sample Size

In each of the four sites per region, four FGDs each comprising 12–15 participants were held with backyard chicken farmers and other poultry value chain actors. The participatory epidemiology tool was applied to one mixed-sex FGD with farmers while the value chain assessment tool was applied to one mixed sex, mixed-occupation FGD with poultry value chain actors comprising chicken traders, chicken feed traders, veterinarians, veterinary drug stockists, and chicken farmers. The gender tool was applied to two sex-disaggregated FGDs with women and men smallholder chicken farmers. The farmers and value chain actors who participated in the FGDs were randomly drawn from lists generated by the village chiefs in collaboration with agricultural extension staff in each location. For the poultry value chain actors, snowball sampling was used to identify the participants invited to the FGDs. We stopped recruiting FGD participants when we reached the principle of saturation (i.e., no new information will emerge from the discussions). A total of 64 FGDs were held, comprising 976 value chain actors (**Table 2**). Women made up 45 percent of all participants. The value chain assessments were held between December 2019 and May 2020.

Conducting the Interviews

Each FGD was facilitated by two local enumerators who spoke the dialects of the communities and were drawn from the study regions. All enumerators were trained by experienced project scientists prior to the start of the fieldwork. The FGDs were conducted using open-ended semi-structured questions (focused on the broad topics listed previously) and in ways that allowed participants to express different opinions during the group discussions. Participants in all three FGDs were encouraged to discuss the solutions they considered relevant to addressing challenges they had identified in the smallholder poultry system. In each FGD, one enumerator facilitated the discussion and the other took written notes of the discussion. Discussions were also recorded digitally. One project scientist was present in each of the FGDs to oversee the process and ensure all emerging information was explored as appropriate. Consent was obtained

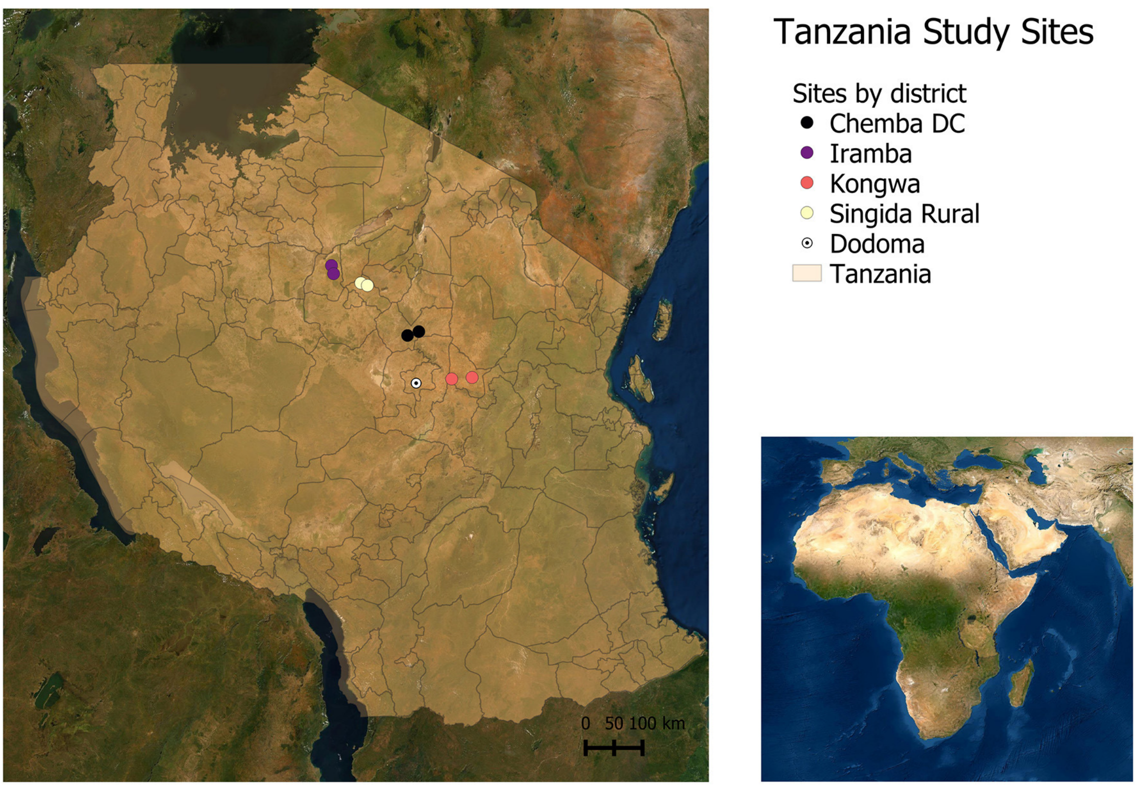

FIGURE 1 | Study sites in Tanzania.

by FGD participants before the start of the discussion. During the FGDs the research team provided refreshments and reimbursed participants for expenses they may have incurred to come to the meeting site.

Data Collection

We detail here the data collection processes using the three value chain assessment tools. The results we present following are data that that the research team considered beforehand to be directly relevant to understanding the potential for improved delivery of animal health inputs and services in the village poultry systems studied. Detailed analyses of the health challenges facing the chicken production systems and of more general issues of access and delivery of health inputs and services and value chain upgrading, which also emanated from the data, are the focus of complementary results.

Participatory Epidemiology

The participatory epidemiology FGDs made use of proportional piling, wherein participants collectively distributed piles of (seed) counters into designated categories according to the frequencies with which they believed certain phenomena/events to occur. The method was used to elicit for communities represented in the FGDs, information on the relative importance of chicken confinement types, timings and volumes of movements in and out of local chicken flocks (e.g., through purchases and deaths) and the reasons for such events (e.g., death by disease or predation). Listing methods captured the range of husbandry practices that farmers in the area followed, while seasonality

TABLE 1 | Poultry value chain assessment sites.

Country	Region	District	Site for the VCA/villages
TANZANIA	Singida	Iramba	Old Kiomboi
			Ulemo
		Singida Rural	Mtinko
			Ikhanoda
	Dodoma	Kongwa	Sejeli/Mbande
			Kibaigwa
		Chemba DC	Gwandi
			Farkwa
GHANA	Northern	Kumbungu	Kumbungu
			Gbullung
		Savelugu	Diare
			Savelugu
	Upper East	Bolgatanga Municipal	Nyariga
			Kalbeo
		Bawku West	Zebilla
			Kukore

Source: field work.

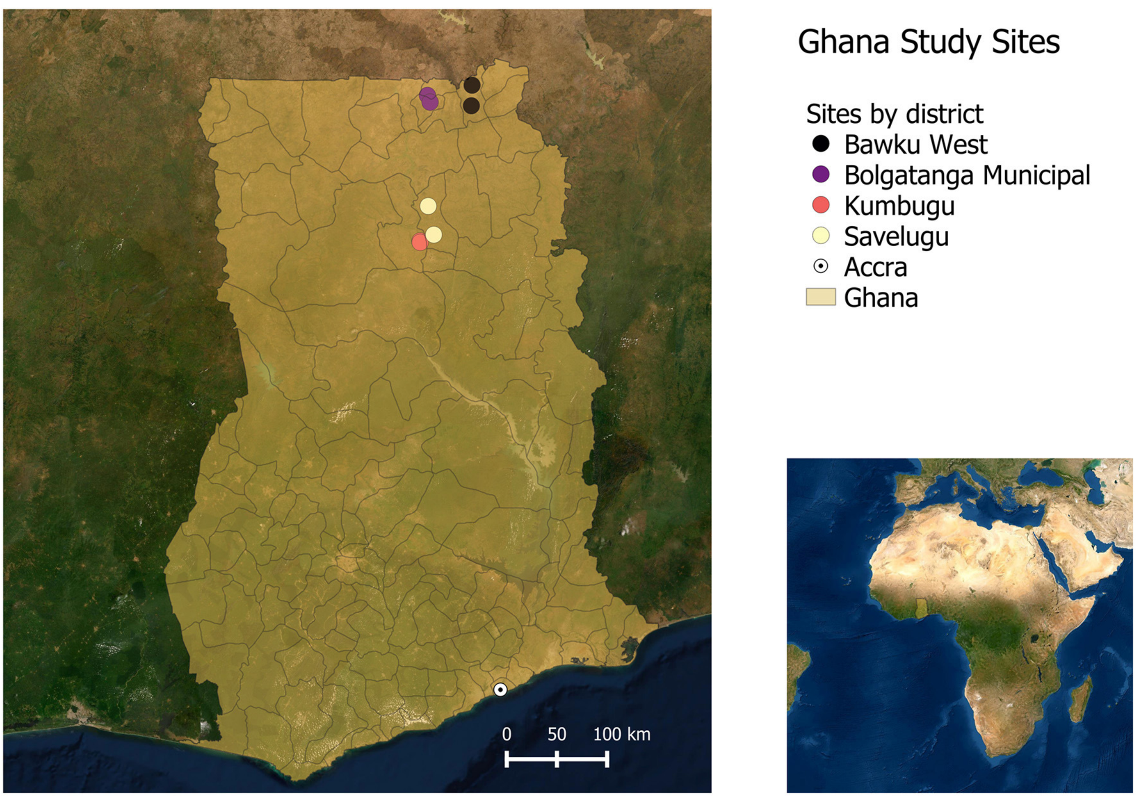

FIGURE 2 | Study sites in Ghana.

TABLE 2 | Breakdown of focus group participation by gender.

FGD focus	Tanzania	Ghana
Participatory epidemiology		
Men	71	58
Women	67	64
Gender*		
Men	100	115
Women	86	98
Value chain		
Men	104	92
Women	66	55
Total	494	482

*Men and women groups were interviewed separately in the gender FGDs.
Source: Field work.

calendars were used to record participants' recall of the season occurrences of different diseases. Simple and pair-wise ranking were used to prioritize listed diseases in order of their perceived importance to chicken production in the communities. Open-ended questions were used to elicit information on the farmers' management of diseases, including vaccinations of healthy birds and disposal of bird carcasses.

Value Chains

The value chain FGDs included a mapping of the local chicken value chain, wherein participants collectively placed on a large blank chart the names by function, of various actors in the local chicken value chain. Markers were placed on the chart to represent the relative positioning of actors within the flow of product (chicken) through the system. Details such as geographical location and prices were then written on the chart next to the markers. For example, [live chicken, Gbullung, 20 cedis] could be written next to the marker for farmer, and [live chicken, Accra, 45 cedis] next to the marker for major live bird retailer. Participants were guided to reach consensus on where lines and arrows were to be placed that showed the relationships between actors, and direction of flow of products or services. Sub-groups of the FGD participants, by their value chain roles (e.g., traders, farmers, and veterinary input providers) identified at the start of the session, were asked function-specific questions so that, for example, farmers could respond on questions about flock mortalities while mainly traders disclosed price margins. All value chain actors were however encouraged to provide their perspectives on issues, even if these were related to nodes of the value chain different from the ones(s) they indicated that they primarily engaged in. The range of questions about the local poultry system was thus discussed among the whole group. Narratives showing both agreement and disagreement of participants within and across the sub-groups (e.g., farmers, traders, veterinary service providers) were noted.

Gender

Participants in the gender segregated FGDs started their sessions by collectively filling in calendars that captured the daily and seasonal time use of women or men farmers. We explored patterns of women and men participation in the poultry value chain by asking participants to detail a typical day for them, in half hour slots, and with a focus on poultry activities. We asked how this day changed over the season. We recorded main differences in a typical day among participants and explored the reasons behind these differences. The session then proceeded in a guided discussion format where the respondents discussed amongst themselves on topics related to challenges they faced in accessing inputs and markets, specific challenges brought on by poultry diseases including ND and their perceptions of the impacts of ND and other poultry diseases on different household types, and on different members within the households. To explore gender-based challenges in accessing poultry inputs and markets we asked all participants to list the main challenges women faced, describe in detail such experiences of challenges, and discuss why the challenges existed. We asked the same questions about the men. We used a similar approach when asking about challenges associated with poultry diseases.

Data Analysis

Overview

Data from the focus group discussions were collected and noted in notebooks. As the data collection tools and resulting data varied somewhat in content, format, and volume (32), we analyzed outputs from the three FGD types separately. This section describes the data analysis process by focus group type. The outputs from the analyses were afterward collated and are jointly presented by theme in the results section.

Analyzing Data From the Participatory Epidemiology FGDs

Data in form of prioritized lists (e.g., poultry diseases) and tables (e.g., flock dynamics generated using proportional piling) were entered into excel sheets for analysis. Transcripts from the group discussions, recorded in the notes as direct responses to the survey tool's guiding questions, were similarly uploaded into excel sheets. These data were organized (e.g., using the Find, Sort, Select and File features) using Excel. The data were examined to identify emerging patterns common among women and among men, across communities and by country. Consensus was analyzed, and patterns were collated and interpreted. We indicate contradicting views that may have emerged from the discussion, when appropriate.

Analyzing Data From the Value Chain FGDs

Some of the data from this FGD type were captured in charts, tables and lists. These were entered into Excel sheets. The interview transcripts, which had been documented as direct responses to the survey tool's guiding questions, were also uploaded into Excel. For each question from the survey tool, individual and group responses were uploaded, and tagged such that they could be associated with specific sites, e.g., Gbullung, Ghana, and respondents, e.g., Trader T2. Responses to survey questions pre-determined to be related to disease management and the delivery of veterinary inputs were extracted and grouped by theme. These included the narratives on value chain actors' experiences and management of poultry diseases, and on access to veterinary inputs and services. The rest of the data were scanned using key word searches to identify other text relevant to the themes of interest. For example, the additional search will identify a discussion on disease impacts that may have emerged while farmers discussed their access to chicken feeds. The final collated data were then examined to identify patterns emerging from the different value chain nodes and across communities. This simple approach to collating, organizing, and analyzing the data using Excel was considered quite effective for the value chain FGDs as these had not produced voluminous amounts of qualitative data (as had the gender FGDs below, for example).

Analyzing Data From the Gender FGDs

The interview transcripts were uploaded into a qualitative analysis software package (NVivo Version 11). Transcripts were coded by a team of two research analysts and a gender scientist. Coding was based on a codebook developed by the team initially in a deductive manner (i.e., based on key themes from our research questions and team discussions during fieldwork). We then also conducted open coding, in which common themes that emerge from the interview notes are identified and assigned codes. Open coding allows new themes recurrently mentioned by the respondents to be captured. Discrepancies in the coding among the team members (such as length of text included under a code), were identified through NVivo, and harmonized. The coded data were examined to identify emerging patterns common among women and among men. We also checked whether other social markers, such as age, education, and marital status, could explain differences among women and among men. Consensus analysis was undertaken, and patterns were synthesized and interpreted as we present below. We indicate contradicting views that may have emerged from the discussion, when appropriate.

RESULTS

Socio-Economic and Production Characteristics

The age of participants from Ghana was from 19 to 80 years, with an average of 42 years. Illiteracy level was high at the study sites in Ghana, with 60% of the participants (and 79% of women participants) having no formal education. Median age of participants in the different FGDs in Ghana was 32–52 (**Table 3**). The farmers mainly raised local breeds of chicken, with flock sizes ranging from 2 to 180 birds. Most of the farmers practiced free-range feeding with a few supplementing using purchased feeds. The average age of the participants from Tanzania was 42 years, ranging between 18 and 87 years old. Most of the participants (69%) had primary level education and 22% had secondary education. Median age of participants in the different FGDs in Tanzania was 28–53 (**Table 4**). The farmers owned local chicken breeds with flock sizes ranging between 2 and 100 birds. A few of the farmers also reared improved dual-purpose breeds of chicken on commercial basis with a flock size of more than 200 birds. Most of the farmers practiced free-range feeding with some supplementation through purchased feeds. The main constraints and impacts of the different disease management strategies are described in detail following. We report interesting within- and across-group differences in perception as they were observed.

Constraints to Animal Health Care in the Village Poultry Systems

Presence of Poultry Diseases

In addition to ND, common poultry diseases inferred to be causing morbidity across the study sites of both countries were fowl pox, worm infestation, infectious coryza and coccidiosis. High incidences and impacts of poultry diseases were associated with limited access to veterinary service suppliers and access to veterinary products. These were due to long distances and supply shortages and led to high costs. Low quality of available products and low levels of chicken keepers' own knowledge of poultry health management were also considered major hindrances.

Limited Access to Veterinary Service Providers

Fifty percent of all the farmer groups in the participatory epidemiology sessions indicated shortage of veterinary service providers as a key constraint. Women also complained that their access to veterinary services had declined over time. Participants from the FGDs in Ghana were more likely than the groups in Tanzania to volunteer that they called for the services of a veterinarian to manage Newcastle or other poultry health challenges on their farms. The farmers in the Ghana FGDs also typically had larger flock sizes than those from the study sites in Tanzania (**Tables 3**, **4**). Six (75%) of the groups in Ghana recounted calling on veterinary service providers for preventive care in form of vaccines. They reported that they called in a veterinary officer just ahead of when ND outbreaks were expected to occur. In addition, five (5) of the groups noted they called a veterinary officer to diagnose or treat their sick birds. In Tanzania, 25% reported calling or going to a veterinary officer to vaccinate birds. No group in Tanzania volunteered that they called veterinary officers to diagnose or treat sick birds.

Participants in Ghana stated there were too few officers available and responses to calls for the veterinarian were often delayed. One farmer lamented that "*we call the [veterinary] technical officers when our birds are sick. Most often, they do not respond promptly so we purchase our own medication to treat our birds.*" A veterinary officer noted that most farmers did not vaccinate their birds or did so irregularly. Late intervention could also lead to increased disease incidences and higher bird mortalities. Participants in one group in Tanzania shared their experience that majority of them vaccinated only after seeing that the birds of neighboring households were infected. According to the participants, since by this time their own birds were already likely infected, the vaccine instead accelerated chicken deaths. Participants in Ghana recounted times that veterinary officers responded to calls but declined to vaccinate as they suspected a Newcastle disease outbreak had already started. In these instances, bird owners were advised to purchase medications for treatment.

TABLE 3 | Socio-economic make up of focus group participants in Ghana*.

	Kumbungu	Gbullung	Diare	Savelugu	Nyariga	Sherigu	Zebilla	Kukore
Women FGDs								
Total #Participants	15	15	12	9	12	11	7	17
#Primary education or higher	3	3	1	1	1	5	2	4
Median age	35	42	45	52	55	34	36	40
Median flock size	16	17	23	40	13	11	25	12
Men FGDs								
Total #Participants	15	12	15	15	15	12	17	14
#Primary education or higher	9	5	1	6	2	2	5	5
Median age	32	38	39	40	n/a	43	46	34
Median flock size	27	68	30	40	n/a	48	27	45
Participatory epidemiology FGDs								
#Participants	15	15	15	16	15	15	15	17
Median age	30	30	45	35	50	40	43	42

**Data presented are for farmer-focused groups only. Data from mixed occupation value chain FGDs are not included.*
Data on median flock size is missing for the mixed farmer groups in Ghana.
Source: Field work.

TABLE 4 | Socio-economic make up of focus group participants in Tanzania*.

	Old Kiomboi	Ulemo	Mtinko	Ikhanoda	Sejeli/Mbande	Kibaigwa	Gwandi	Farkwa
Women FGDs								
Total #Participants	14	13	10	11	10	10	10	10
#Primary education or higher	14	13	10	11	10	9	10	10
Median age	42	46	42	38	40	29	44	39
Median flock size	15	10	8	10	11	11	9	8
Men FGDs								
Total #Participants	13	14	10	11	11	15	12	13
#Primary education or higher	12	14	10	11	10	15	12	13
Median age	53	42	28	36	35	29	46	38
Median flock size	15	17	23	10	30	11	16	10
Participatory epidemiology FGDs								
#Participants	16	18	14	21	15	21	18	14
Median age	48	41	32	44	40	44	42	40
Median flock size	17	14	11	22	11	15	10	11

**Data presented are for farmer-focused groups only. Data from mixed occupation value chain FGDs are not included.*
Source: Field work.

Low Availability of Veterinary Medicines and Other Products

In both countries, limited local availability of poultry vaccines and veterinary drugs was reported by 43% of the farmer groups involved in participatory epidemiology group sessions. In most cases the veterinary shops were in towns far from the poultry farmers. In Northern Region of Ghana, poultry farmers must travel to Tamale town to be able to purchase veterinary drugs. Women in both countries emphasized their limited access to veterinary drugs and vaccines (and other inputs) because of their limited mobility. The constraints made them dependent on their husbands or other male relatives to access inputs and veterinary services. Women in Tanzania listed agro-veterinary shops being far from their villages and therefore not accessible. Many women in Ghana stated they were not aware of shops where they could purchase veterinary inputs. In some cases, vaccines were not available even in the veterinary drug shops at the far locations. This was reported by a group from Old Kiomboi in Singida region in Tanzania. Participants in Ghana noted that the technical officers, who are government agents, did not receive government-issued supplies and privately procured vaccines to render veterinary services in rural areas they served. Some of the basic requirements for poultry disease prevention and control, such as disinfectants for use in the chicken coops, were also not available to the small-scale chicken farmers. This was reported by two groups in Upper East Region in Ghana – Nyariga and Zebilla.

High Costs of Veterinary Products

Women in both countries indicated the lack of cash to purchase veterinary inputs or services even when these were available locally. Issues were raised by men and women farmers regarding the cost of vaccine administration, particularly for small flock sizes. A farmer indicated that "*the vaccines are usually for a [large] number of birds and if your birds are fewer and you call the veterinary officer, he is not always willing to come.*" It was noted that the vaccines came in large packaging containing several doses and there had to be many birds available before vaccination could be done or unused vaccines could go to waste. According to the participants, large dosage packaging is uneconomical to farmers with fewer birds as they are charged more per bird for vaccines or treatment. One farmer noted paying ten times (Ghc 5.00) the usual amount (Ghc 0.50) for treating a single fowl (Ghc = Ghana Cedis; 1 US$ = 5.35 at time of study). Across the different sites in both countries, women typically owned smaller flocks than the men (**Tables 3**, **4**), potentially making them more exposed to the higher costs imposed on smaller flock sizes.

Low Quality of Veterinary Products

The prevalence of poor-quality veterinary drugs and vaccines was reported in two groups in Tanzania—Ulemo and Kibaigwa—and by both women and men. The drugs and vaccines were reported as not effective as treatment measures or for enhancing immunity against diseases. Men and women participants in Tanzania reported that they sometimes lost their birds to ND even after vaccinating for the disease. The participants noted that quality assurance systems are weak, with minimal or no regulatory inspection and testing of veterinary drugs and vaccines for quality. The focus group participants also identified challenges with vaccine storage and with the vaccination process. In the case of ND, a trader in Tanzania suggested the challenge could be with how vaccines were stored by the distributors, to which an input supplier angrily responded *"I am not the one ensuring (poor) quality of vaccines but producers themselves do not store the vaccines properly*".

Inadequate Knowledge of Good Husbandry Practices

In both countries, lack of farmer education on appropriate husbandry practices was reported by 71% of the groups, cutting across both countries. This was largely attributed to poor access to veterinary extension. Coupled with poor access to quality veterinary drugs, participants indicated that it resulted in indiscriminate use of drugs in the backyard poultry systems. Men and women farmers in both countries opined that they lacked knowledge on the correct veterinary drugs to use, where to get them, and how to administer them. They indicated that they also lacked knowledge on disease management and poultry management in general. Men in the gendered farmer groups in Ghana opined that women farmers had limited formal education and so suffered these constraints even more. Producers in a value chain FGD group in Tanzania conceded that they sometimes diagnosed poultry diseases by themselves and confused ND symptoms with those of typhoid. A trader lamented their exclusion from trainings that farmers obtained on poultry or poultry disease management. Participants in both countries said government livestock ministry officers or representatives from non-governmental or religious organizations had visited their villages/wards to train them on more general poultry management but these were not regular or adequate.

Impacts of Poultry Diseases on Backyard Poultry Systems

Chicken Mortalities

Bird deaths were suggested as the major impact of poultry diseases in the communities represented. Both men and women farmers indicated that they could suffer total loss of their flocks. One farmer from Diare and three from Savelugu recounted experiences of losing their entire flock. However, all (8) farmers in the mixed value chain actor group at Kumbungu declared they had never suffered total bird losses since they vaccinated appropriately, following government department schedules. Bird losses were experienced by both farmers and traders. Farmers were considered most affected in the Zebilla and Kukore groups, while traders were seen to be most affected in Diare. In three of the mixed value chain actor groups, i.e., at Kumbungu, Gbullung and Savelugu, farmers and traders disagreed about which value chain actors were most impacted by disease-related mortalities, each actor group claiming they suffered the most. There seemed to be agreement in the Nyariga group that farmers and traders suffered equally from the losses. The focus groups in Tanzania also identified both producers and traders as being severely impacted by the effects of poultry diseases. Participants in four groups, i.e., Old Kiomboi, Mtinko, Ikhanoda, and Sejeli / Mbande agreed that farmers were most affected, while those in Ulemo, Kibaigwa, Gwandi and Farkwa thought traders were as affected as farmers.

Impacts on Farmers

Farmer losses were linked to reduced stocks and the loss of expenditures made on feeds. In addition, producers received lower prices for birds they sold when there was a disease threat (e.g., in the dry season) or known outbreak. The indirect effects were felt throughout the household since cash or in-kind receipts from bird sales are typically used to meet food expenses, the payment of children's school fees and household bills, and agricultural activities such as hiring tractors. Men participants also indicated that they used their poultry animals to acquire other animals, particularly goats through barter trade, and as dowry and gifts. Frequent bird deaths from disease, they said, made the business of raising birds unsustainable. Farmers got discouraged and did not want to continue raising birds. They were also hindered from expanding their operations. A producer in Farkwa in Tanzania noted, "*without vaccines, good feeds and medicines we cannot raise our birds commercially.*" Men farmers in Tanzania said they bore the added responsibility within the family to purchase the drugs to treat sick chickens, and when the chickens died, they still needed to provide for the family. A participant said "… *a man (breadwinner) is affected most because he is responsible for buying meat if the chickens are infected or die.*"

Impacts on Women Farmers

Many participants opined that women farmers were more severely impacted by the poultry disease outbreaks and threats. This was the consensus position of four of the groups of mixed value chain actors in Tanzania, i.e., Old Kiomboi, Ulemo, Sejeli/Mbande and Farkwa. The groups suggested that the women typically lacked the funds or collateral to access loans and were unable to revive their businesses after disease-related losses (Old Kiomboi). Women also bore major responsibilities for the family's expenditures on food consumption and other needs such as electricity and relied on their earnings from poultry to meet these needs. A woman farmer in Gwandi highlighted how important the incomes from poultry were to the women, stating *"over-dependence on the men for financial support might lead to conflicts 'magomvi'."* Women were also more directly impacted by the loss that bird deaths represented to farm inputs (chicken manure) and as a household food (protein) source. Women were said to slaughter some of the chicken to support household nutrition, particularly when funds were scarce to buy red meat. The women farmers thought their income losses in relation to poultry disease outbreaks were further compounded by the inability to negotiate live bird prices as well as the men.

Traders and Other Actors

Traders listed the main impacts they suffered from bird deaths as reduced earnings and disrupted businesses. Like farmers, traders could experience bird losses of 60–100% during a disease outbreak. Traders said that they lost unearned income in addition to their investments. A trader in Gbullung in Ghana lamented "*when we buy the birds and they die before we sell them, we lose both profit and capital*" It was not unusual with traders, they said, for many birds to die even before they reached the market. The high disease incidences (and impacts) were perceived to be associated with the common practice by traders in the communities of mixing birds from different sources as they were aggregated for/transported to market. The perception of one participant in Ikhanoda was that traders were not very capable of detecting the (Newcastle) disease and suffered greater losses as a result. Producers could sell off unhealthy birds to unsuspecting traders without detection. Other actors along the value chain indicated they were also affected by there being fewer and smaller sized birds available to purchase. The demand for poultry feed declined during an outbreak (affecting poultry input sellers) while prices of poultry products increased (affecting processed food retailers and consumers).

Current Strategies to Manage Poultry Diseases or Mitigate Their Impacts

Filling Gaps in Veterinary Inputs and Services

Only four of eight mixed-gender participant groups in both countries, consisting of both men and women, reported that they purchased medicines or vaccines from veterinary stores. In the absence of proper veterinary drugs, both men and women producers and traders reported resort to the use of local formulations of traditional herbs such as moringa, aloe vera and pepper, as well as human drugs and food products to "treat" sick birds. Women farmers in Ghana said they used human antibiotics in lieu of vaccines for their birds while a farmer in Gwandi, Tanzania said he fed fresh milk in small quantities to chicken as medicine. Participants noted that most of the affected birds treated for suspected ND using home-based therapies still died. Men and women farmers also practiced local adaptations of biosecurity measures, including spreading ash in chicken coops to avoid the spread of disease after there had been bird deaths. A group in Tanzania made up of men farmers indicated that while the women farmers relied on traditional herbs or human drugs, they (men farmers) used veterinary drugs purchased from the shops. Although some farmers got their birds vaccinated for ND, this, by their own accounts, often did not adhere to the (regulatory government department's) guidelines.

Women from Tanzania mentioned organizing vaccination days when they would gather their small flocks and collectively use up large packages of vaccines, making them more affordable per dose/person. A men's group also in Tanzania offered that they had used social media platforms to coordinate group vaccinations for their birds. In Sherigu, Ghana, a study participant noted their use of community-based animal health personnel. Locals within the community were able to acquire some know-how and provided support to services of government veterinary and livestock officers. The producers considered this development a successful/desirable local intervention.

Bird Sales or Slaughter

A common practice among men and women farmers in the study communities was to sell off healthy birds ahead of the dry season or (ND) outbreak season. A male farmer in Diare opined that, given the high veterinary costs to those with fewer birds, "*the best solution sometimes is to slaughter that single fowl for household consumption.*" In one group in Ghana, all the participants indicated that they sold off most of their fowls before the onset of the season, to prevent complete losses. Some women however complained that gender norms discouraged women from fully exploiting this option. A woman from Kukore explained: "*Women in this community cannot carry their own chicken to the market to sell because it is culturally prohibited to do so. When a woman carries a chicken to the market, it can result in divorce.*" According to the women, the man could decide when to sell their wives' chickens, and controlled bird sales and proceeds from sales. The men agreed that a man could sell off his wife's chicken even if she disagreed with the sale.

As we have indicated in the discussion on impacts above, participants raised the issue of some farmers not being transparent about the health status of their flock, effectively shifting some of the potential bird losses through trade. A study participant in Farkwa however pointed out that once traders were aware of a Newcastle disease outbreak, they stopped purchasing birds in the general area and producers were left to absorb eventual losses. One group in Ghana noted that the consensus in their community was that sick birds could be slaughtered and consumed within the household, but not sold to traders or food vendors. There were no reports at any of the chicken farming communities of households slaughtering healthy birds for consumption, in anticipation of disease outbreaks.

Interventions Suggested by the FGD Participants

Increase Supplies of Vaccines and Veterinary Drugs

Participants in Tanzania noted that vaccines need to be made promptly available and that this was the responsibility of the government, working through extension officers and farmer co-operatives. There was a call for vaccine manufacturers to better adhere to quality standards and on government to perform improved quality assurance. Veterinary vaccines and drugs should undergo regular inspection and testing for quality. Women farmers asked that veterinary shops be brought to the villages. According to participants, the government needed to coordinate a vaccination program to be implemented by extension officers who will provide regular farmer trainings on vaccination and more general poultry health management. Producer cooperative groups and village community meetings were some mechanisms that village chicken producers thought could be utilized to facilitate these. Some participants in both countries thought that governments or other entities should facilitate regular access, while the costs of vaccines, drugs and farmer education could be borne by them, the end users. Others suggested that veterinary drugs, vaccines, and other inputs such as strong disinfectants needed to come at subsidized prices to village poultry producers.

Strengthen Livestock and Veterinary Extension

In both countries, participants offered that the extension services to poultry producers needed strengthening. Men and women farmers highlighted the importance of education and training regarding vaccination and that they needed to adopt modern methods of poultry management. The establishment of demonstration farms and increased connections to farmer co-operative groups were identified as important. Respondents thought the government livestock departments needed to employ more extension and veterinary personnel, including at the ward/village level. Women farmers in Tanzania asked that extension officers be allocated permanently in each village to support farmers. This service, they opined, should extend to odd hours as they sometimes faced challenges with poultry diseases late in the night. Women farmers in Ghana also asked that community volunteers be trained to assist farmers with urgent treatments for their chickens, and that more veterinary officers be recruited to expand the coverage of farming families. Men and women respondents in Ghana sought more oversight of field officers deployed from the Ministry and asked that there be increased consultations with the communities regarding the recruitment and deployment of officers.

Improve Farm Management

Farmers in both countries noted that they needed training on poultry and disease management and needed to adopt improved poultry technologies. Women farmers in Tanzania and Ghana said they needed chicken housing that could better protect their birds and were easier to clean. The farmers also highlighted the needs for improved access to good chicken breeds that were resistant to disease, and to credit to purchase poultry production inputs. All farmer groups agreed they will be willing to raise birds with increased natural resistance to ND even if it did not confer total immunity. They indicated they would pay (varying amounts) more than current bird prices to access such breeds. Men farmers in Tanzania indicated their preferences for contract farming, and for better access to inputs, and to markets. Participants in Tanzania noted that government, private sector and NGOs could engage more to provide information and training to end what they identified as a patriarchal system within their society, that was present in the village poultry value chain and constrained poultry development.

DISCUSSION

The poultry health delivery systems we investigated in Ghana and Tanzania are known to face several constraints that limit their effectiveness. Disease-related constraints prioritized by the nearly 1,000 respondents in our study highlighted the limitations in management of infectious chicken diseases as being largely in the areas of availability, access to, and quality of vaccines and other veterinary inputs and services. These findings echo previous results for village poultry systems in Ghana (40) and Tanzania (41). Our study however provides additional context into how these constraints are experienced, differently, by diverse actors in the poultry systems and countries of the study.

There Is Interest Among Farmers to Adopt Appropriate Technologies

While men and women farmers reported that they sometimes lost birds despite vaccinating, the overall narrative was that they got good results with proper vaccination, and expected that regular use of good quality vaccines could protect their flocks from disease (particularly ND)-related losses in the future. This result suggests that farmers perceive good vaccines to be beneficial for poultry production in their communities. It is an indication of possible interest amongst farmers to adopt vaccine technologies if they consider them of good quality. Vaccine delivery systems that will be compatible with the communities studied will however need to not only circumvent the systemic issues constraining access and quality of vaccine, but do so in manners that recognize the peculiar needs of key constituents such as poor farmers and women farmers.

Examples from East Africa, of dairy hub innovations that facilitate access of smallholder farmers to both inputs and markets, including through providing access to low-cost (appropriate) chilling technologies (42), may have lessons for improving the delivery of animal health inputs and services to the farming communities in our study.

Increased Focus to Be Paid to Poorer Farmers and Women Farmers

Long distances and high fixed costs, arising from high transportation costs and in the case of vaccines, products that come packaged in large dose batches, mean that current limitations in access are felt much more acutely by those with fewer resources. In Tanzania, particularly, chicken producers reported needing to patronize input suppliers at far off locations to obtain vaccines and veterinary drugs. This option was available to the better resourced of the chicken farmers who could make the journey, and in the case of heat-labile products, those who could maintain the vaccine's cold chain. For most other producers, the needed inputs remained largely unavailable. Women tend to fall more into this latter category. In the communities studied, women were less likely to have the needed infrastructure (e.g., transportation) or the cash to pay for veterinary inputs and services. They were further hindered (e.g., in parts of Ghana) by cultural norms that prevent them from managing their limited resources using mechanisms (e.g., market sales) that are readily available to others. Women also seemed more adversely impacted by the system failures, as they relied more on the proceeds from poultry keeping compared to men.

Strengthen Farmer Capacities to Influence Outcomes

Focus group participants rightly prioritized the lack of relevant education on infectious chicken diseases and poultry management more generally, as major hindrances to their poultry production. Poor training of farmers (in poultry/disease management) limits the effective use of whatever inputs and services are available or accessible. This is being addressed in some communities through farmer education programs by NGOs and others, but it seems not in a coordinated or far-reaching manner. At the Ghana sites, the tendency was for producers to seek out the direct services of (typically government-appointed) veterinary officers who were largely unavailable and had limited coverage of the rural areas. Low levels of formal education and limited access to technology (e.g., owning a mobile phone) were heightened for women at these sites, and could explain, at least partly, the high dependence of such communities on direct assistance from veterinary departments. Chicken producers with very low levels of education and/or access to technology face particularly steep challenges, as they do not have the advantage of being able, for example, to read medicine labels, or readily access poultry farm and disease management information online by themselves.

Low Literacy Areas to Benefit From Changing Dynamics in Education

Some participants in Ghana suggested that human resources from within the rural communities (e.g., youth who typically have more formal education than their parents) could be trained to provide back-up to the services provided by veterinary officers. Although earlier work in northern Ghana had shown clear preferences of local chicken producers for government para-vets, due mainly to higher transaction costs and poorer performance of community animal health workers (40), our research will suggest an important nuance. In areas with extremely low levels of education, local personnel with formal education, if adequately trained, could immediately fill yawning gaps in the provision of animal health services that need not so much technical expertise, but the capacity on the part of the farmers to engage meaningfully with that expertise. The engagement of skilled local persons to support in community farm management and animal health delivery potentially reduces pressures on senior expertise. It could also double as opportunities for skills development and at least part-time employment for rural youth. Such local involvement will however need be conducted under close supervision of the veterinary services departments to ensure quality of services and maintain viability of the model.

Build on Early Advances in Collective Action

Communities being able to self-coordinate to execute bulk vaccine purchases and vaccinations is already occurring and seems to hold additional promise for the future. Well-coordinated farmer cooperatives may be better suited to facilitate farmers being able to access reliable supplies of inputs and lower their current high costs. Bulk demand of vaccines, for example, could attract private sector involvement in ways that the current dispersed and uncoordinated vaccine demand from rural areas has been unable to. The high rates of attainment of basic education and widespread access to mobile telephone technologies at some of the studied communities (in Tanzania, particularly) makes for good candidates for scaling such intervention. Existing platforms of mobile technology and smart phones could be used to more readily signal, mobilize, or synchronize demand for veterinary services in village chicken production in rural areas. In the Ghana sites where rates of formal education and access to mobile phone technology were found to be extremely low, the focus of intervention could be on the empowering of target individuals and small groups within the communities, and support for the building up of key informal networks and dissemination cells around these individuals/groups. The study by (43) will suggest that the flow of professional-level knowledge by early vaccine adopters within the community has strong influences on increasing overall adoption amongst potential users. There may also be a case to improve the possibilities for learning across sites, for example by connecting farmer networks across communities and possibly countries.

Integrate Traders Better in Disease Management

Although traders are usually not the target for capacity development on infectious disease management in village poultry systems, the results from our study will suggest that traders have real reasons to engage in activities that will ensure farmers can obtain and use good quality vaccines, veterinary drugs, and other inputs they need. Traders and aggregators were found to handle live birds for considerable amounts of time and suffer substantial economic loss during disease outbreaks. Support to traders could be in capacity development for animal disease management but could also be more market oriented. Business models targeted to ensuring the delivery of veterinary inputs to smallholder producers will benefit from accounting correctly for the incentives of live bird traders in the system. Strategies to involve traders in the supply chain for veterinary inputs or services will however need to be well designed as traders in some communities were already perceived to hold unbalanced power. Care may need to be taken that traders are not in addition perceived to be displacing primary producers.

Expand Scope for Private Sector and Market Opportunities

As with other studies addressing historical and institutional failures, many of the solutions directly proffered by the FGD respondents pointed to a larger role for the government. There may however be little appetite, despite indications of positive benefits to adopting communities (3) for increased public spending on wide-scale vaccination or similar programs to improve animal health care delivery to village poultry systems. It becomes imperative to explore the potential for private sector involvement, including the incentives for end users to take up the costs and/or coordination of vaccine and other veterinary input supply and use in village systems. In the case of *peste des petite ruminant* (PPR), a viral disease of small ruminant animals affecting mainly smallholders, a recent study showed that better communication on vaccine benefits through targeted information dissemination, and timely availability of vaccines with assured quality increased the willingness of farmers to vaccinate or pay for vaccines (44). Similar assessments will need to be completed to better understand what the cost implications will be for meaningful private sector engagement in the study communities in Ghana and Tanzania, and what incentives exist (and for whom) within the system.

In addition, interventions are needed, including business models, that improve the incentives for various value chain actors to adopt effective disease management within processes and outcomes that they control. Introducing mechanisms for livestock traceability should improve quality control in the village poultry system. This potentially could address concerns about, for example, local farmers selling off diseased birds to unsuspecting buyers. Traceability has however been a difficult concept to concretize in low resource agricultural and food systems, particularly outside of export value chains. In the context of the village poultry systems, the infrastructure that will be required to control, regulate, or monitor chicken production, sales or slaughter at the individual farmer level may not currently exist. However, early studies show promise of the presence of demand- side incentives to produce better quality animals and livestock products in low income countries, and work is ongoing to better understand what regulatory mechanisms align well with such incentives (45).

CONCLUSION AND NEXT STEPS

Vaccines and veterinary drugs for the management of common infectious poultry diseases such as ND, are largely effective and readily available in urban areas and at affordable prices. However, long distances, poor infrastructure, and low business potential in rural areas prevent private suppliers from investing in these areas where most poultry producers reside. Inadequate education and training on the part of the producers reduces effectiveness of disease preventative and treatment options when they are available. Economic (e.g., lack of transportation means) and social prohibitions (e.g., restrictions on the engagement of women in certain economic activities) further limit the access of many women to veterinary inputs and services.

Poultry health care delivery options with high chances of success in the studied communities will be those that focus mainly on the delivery of quality veterinary products and services that are affordable, enhance supply of quality drugs and vaccines in rural areas and are tailored to reach poorer producers and more women by e.g., compensating for their reduced mobility, and access to information and markets. They also need to address trader as much as farmer/producer concerns. To improve management of infectious poultry diseases in developing countries, systems of veterinary inputs and services provision can build on what exists while better taking farmer needs and perceptions into consideration. Community-based approaches and increased use of technology such as mobile phones have much to offer, as do increased engagement and cooperation between government, non-governmental organizations, private sector, and cultural institutions, and appropriate investments by private enterprise and farmers themselves.

Our study investigating the perceptions of nearly 1,000 farmers and other value chain actors in Ghana and Tanzania, on interventions needed to address animal health challenges in village poultry systems largely agrees with the literature. This study highlights the need to expand coverage to better reach women, particularly as they are the majority of small-scale chicken farmers, and emphasizes the need for solutions to include others such as traders that are usually not involved throughout the production process but are very much adversely affected by the outcomes of poor poultry health at farm level. It also calls attention to heightened challenges that rural chicken producing communities are up against that have lower literacy rates and/or more limited access to information and communications technologies compared to other poor communities. A new project in Ghana is testing approaches to support women animal health service providers in chickens (and goats) as a way of reaching women farmers[1]. The project is adopting a transformative approach that aims to address some of the gender norms that the respondents of this study mentioned as limiting their ability to effectively raise chickens.

New quantitative analyses are needed to understand (1) what types of producers will be willing to pay market prices for improved veterinary inputs and services (e.g., using consumer choice experiments)—we found divergences in thought about whether the farmers and other value chain actors should bear full or partial costs of vaccines and other inputs; (2) to what extent willingness to pay on the part of users will incentivize capital inflows from private providers of vet inputs and services; (3) what society stands to gain by investing in village chicken production vs. other candidates for public investment; and (4) what policy or other government initiatives are needed.

[1]https://www.ilri.org/news/annual-report/ghana-why-the-goats-will-not-die-on-her-watch, accessed 28 September 2020.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee for Basic and Applied Sciences (ECBAS), University of Ghana Ref. No. ECBAS046/18-19. Ethical clearance was obtained in Tanzania from the Office of the Vice-Chancellor, Sokoine University of Agriculture, and research permits for Singida (Ref. No. DPRTC/R/142/Vol. I /42) and Dodoma (Ref. No. DPRTC/R/142Vol. I/43) districts. Informed written consents were obtained from all participants in the study. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DE led the design and writing of the manuscript and contributed to the data analysis. EO and AG contributed to the design of the study, analysis of the data, and writing of the manuscript. TK, YA, GC, JK, FAM, FM, and MD contributed to the writing. JK and HJ assisted with the qualitative analysis. All authors reviewed and revised the manuscript.

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Animal Health Service Delivery in Crop-Livestock and Pastoral Systems in Ethiopia

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Livestock diseases are a priority problem for livestock keepers throughout Ethiopia. Livestock keepers have also singled out poor animal health service delivery, which is largely the domain of the public sector, as the major constraint to improving animal health and productivity. In the current study, we describe the animal health service delivery system and compile from five questionnaire surveys involving 4,162 livestock keepers to characterize animal health service delivery in Ethiopia. The mapping of the animal health service delivery system along the livestock value chain clearly highlights the role of informal animal health services and variations of roles of the private sector. Also, the survey results clearly showed that livestock keepers' access to, use of and satisfaction with animal health services significantly varied across livestock production systems, geographic locations, socioeconomic strata, and service providers. Livestock keepers in crop-livestock and agropastoral systems had 5.5 (odds ratio = 5.453, $P = 0.000$) and 2.5 (odds ratio = 2.482, $P = 0.000$) times more access to services in reference to the pastoral system. In reference to private veterinary clinics, livestock keepers reported higher access to services provided by all the other service providers, particularly to services provided by extension agents, drug shops and CAHWs. Similarly, better access was reported by male than female (odds ratio = 1.098; $P = 0.025$) and wealthier than poorer (odds ratios = 1.40–1.79; $P = 0.000$) farmers and pastoralists. In general, low access to services was reported, 32.7, 25.2, and 19.3% of the respondents reporting access in crop-livestock, agropastoral and pastoral systems, respectively. Effective demand for services was evaluated through proxy variables, namely number of visits to service providers and health expenditures over a year. Highland farmers used the services more often than pastoralists (odds ratio = 2.86; $P = 0.000$), but pastoralists' expenses were significantly higher. Wealth (measured by livestock owned), gender and age also had significant effects on the use of services and expenditure on services. Satisfaction with services was evaluated based on four measures, namely availability (av), accessibility (ac), quality (qw), and timeliness (tm) of services. The average scores (out of 10) for av, ac, qw, and tm were 6.1, 5.9, 6.2, and 5.7, respectively. Principal component analysis was conducted to derive the latent variable "satisfaction" from the four measures, extracted only one factor, indicating the four variables are measuring the same construct (satisfaction).

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Regressing the latent variable satisfaction on the four measures gave significant ($P = 0.000$) b values of 0.22, 0.20, 0.13, and 0.14 for av, ac, qw, and tm, respectively, indicating strong relationships between the latent variable satisfaction and its measures. There was a significant dissatisfaction with the public sector, with average scores of 0.06 and 0.19 for the public and private service providers, respectively. It can be concluded that livestock keepers in remote regions of the country, pastoralists, women, poorer, and older livestock keepers have less access to services. Satisfaction with services is low to medium and the major concerns of livestock keepers appears to be availability and accessibility of services. Based on our findings, we recommend an integrated, multi-sectoral involvement to improve the veterinary service delivery through improved veterinary infrastructure, public-private partnership, and animal health information system across the various livestock production systems.

Keywords: gender, systems, PCA, Ethiopia, health services

INTRODUCTION

Ethiopia is endowed with huge livestock resources comprising of 61.5 million heads of cattle, 33.0 million sheep, 39.0 goats, 59.4 million poultry, 11.96 million equines, 1.76 million camels and 7.1 million beehives. A production of 3.3 billion liters of cow milk, 282.2 million liters of camel milk, 151.47 million eggs and 58.6 million kg honey is being recorded per annum (1).

The livestock sub-sector in Ethiopia plays vital roles in ensuring food security, provision of traction power, generation of rural income and employment at the household level as well as national economic growth through foreign exchange earnings but is also culturally important. However, the contribution of this resource to the national economy is not commensurate to the huge national potential. This mismatch is mostly caused by the widespread prevalence of many infectious and parasitic diseases (2–4) which drastically reduce the production and productivity of livestock through morbidity, mortality and market restrictions (5, 6).

Veterinary services are defined as all the public and private players that implement animal health, welfare measures and other standards and recommendations to ensure effectiveness of the system, under the control of the Veterinary Authority (7). It implies that, strong, transparent and credible veterinary services provided by both, the public and private sector, are necessary for enhancing the performance of animal health systems by mitigating animal disease risks, ensuring sustainable economic development of vulnerable producers, and limiting the public health risks posed by zoonotic diseases. Strong veterinary services also provide confidence for private sector investment from both individual farmers and livestock enterprises across the livestock value chains.

Despite various reform efforts over the last decades, provision of adequate veterinary services to smallholder farmers has remained a serious challenge in Ethiopia. Particularly, the coverage and quality of veterinary services are less than satisfactory across the different livestock production systems (2, 8, 9). On top of this, despite few pilot studies, mostly done for academic purposes, in specific areas of the central highlands, there is lack of comprehensive, well-documented and reliable information regarding the core determinants of animal health services delivery in reference to the livestock production systems across different bio-geographic and socio-economic conditions of Ethiopia. Therefore, a review of stakeholders involved in the provision of animal health related services and a household survey was conducted in 9 regional national states to bridge this gap.

MATERIALS AND METHODS

Stakeholder Analysis

A descriptive analysis of the animal health service value chains in Ethiopia was conducted to provide the context to the detailed quantitative household surveys (Section Household Survey). The analysis was built on comprehensive surveys of actors involved in animal health service provision in eight of the nine administrative regions in Ethiopia (see details in **Table 1**) as well as review of the literature. The literatures consulted included a survey of health service delivery in four administrative regions (10), the Veterinary Services Rationalization Roadmap for Ethiopia (11) and The Livestock Master Plan for Ethiopia (5).

Household Survey

Source of Data

The data for this study were obtained from baseline studies, conducted to collect data for the purpose of evaluating project impacts at the end of the projects, of five livestock development projects in Ethiopia: Drought Resilience of Sustainable Livelihood program (DRSLP I and II), Regional Pastoral Livelihoods Resilience Project (RPLRP), Livestock and Fishery Sector Development Project (LFSDP) and Health of Ethiopian Animals for Rural Development (HEARD) (**Table 1**). The DRSLP, RPLRP (12) and LFSDP projects are implemented by the Ministry of Agriculture (MoA). The DRSLP and RPLRP projects aim to improve the resilience capacity and livelihoods of the pastoral and agro-pastoral communities in Ethiopian Somali, Afar, Oromia, and the Southern Nations, Nationalities and Peoples region (SNNP). The two projects are funded by

TABLE 1 | Source of data and data structure.

Region	Production system[a]	No. of woredas sampled[b]	No. of Households sampled	Project[c]
Afar	Pastoral	6	191	DRSLP I
	Pastoral/AP	7	294	RPLRP
Amhara	Mixed	4	216	HEARD
	Mixed	11	360	LFSDP
Benishangul-Gumz	Mixed	3	90	LFSDP
Gambela	Mixed	1	60	LFSDP
Oromia	Pastoral	12	540	DRSLP II
	Mixed/P	4	241	HEARD
	Mixed/P	16	479	LFSDP
	Pastoral/AP	9	378	RPLRP
SNNP	Pastoral	11	330	DRSLP II
	Mixed/P	9	270	LFSDP
	Pastoral/AP	6	252	RPLRP
Somali	Pastoral/AP	8	371	RPLRP
Tigray	Mixed	4	120	LFSDP
Overall		111	4,162	

[a]*AP, agropastoral; Mixed, mixed crop-livestock system.*
[b]*Four and two kebeles were sampled per woreda for the DRSLP/RPLRP/LFSDP and for the HEARD projects, respectively.*
[c]*DRSLP, Drought Resilience of Sustainable Livelihood program; RPLRP, Rural Pastoral Livelihood and resilience Project; LFSDP, Livestock and Fishery Sector development Project; HEARD, Health of Ethiopian Animals for Rural Development.*

African Development Bank and World Bank, respectively. The LFSDP project, initiated in 2019, is funded by the World Bank to strengthen the livestock and fishery development and operates in the mixed crop-livestock system in the highland and mid-highland areas. The HEARD project is led by the MoA, jointly implemented by the International Livestock Research Institute (ILRI), the Ethiopian veterinary association (EVA), and three regional states (Somali, Oromia and Amhara regions). The project is initiated in 2019 and supported by the European Union. All the five projects are still ongoing, and their impacts have not yet been evaluated.

Sampling and Data Collection

Both purposive and stratified clustered sampling approaches were used to draw representative samples for the household surveys for the projects described above. Sampling was stratified at different stages, namely by livelihood zones (pastoral, agropastoral and mixed crop-livestock systems) and administrative zones at the levels of regional states, woredas and Kebeles (the smallest administrative unit). Regions were selected purposively as per the projects aims and design. The projects covered eight of the nine regions in Ethiopia. Woredas within regions and kebeles within woredas were selected randomly considering the livelihood zones. Households were selected randomly considering gender, age and livestock holdings. The sampling frame and data structure is shown in **Table 1**.

The livelihood systems overlapped with agro-ecological zones, the pastoral/agro-pastoral systems and the crop-livestock zones being located mainly in the lowlands (mostly below 500 meters above sea level) and highlands (commonly above 2,000 m a.s.l), respectively, though mixed crop-livestock production is also found in lower altitudes between 1,000 and 2,000 m a.s.l. The DRSLP and RPLRP projects operated in the arid and semi-arid lowlands, whereas the LFSDP and HEARD projects operate in the highland (above 2,000 m a.s.l), midland and lowland areas (1,000 and 2,000 m a.s.l).

The data were collected using household surveys with structured questionnaires. All the data were collected by ILRI as a baseline for the five projects. The data were collected on various aspects of the households including household demographics, physical assets, livestock holding and composition, crop technology adoption and use, sources of livelihoods, and access to services. The data for the current analysis included household demographics, animal health services, which included the types of services and the service providers, access to services by the livestock keepers, frequency of visits to health service providers, expenditure on services, and satisfaction with the services.

Data Analysis

Both descriptive and inferential statistical analyses were used. For descriptive analyses, the response data were disaggregated by bio-geographic zones (production systems, geographic regions), socio-economic strata (gender, age, wealth status measured by livestock holdings), and the types of service providers. Proportions of the sampled households with the alternative responses (e.g., access or no access to services) within each bio-geographic zone and socio-economic strata were calculated to assess the availability and accessibility of the services and satisfaction of the livestock keepers with the services. Proportions were compared using chi-squared tests.

Access to services was coded as a binary variable (1 = access, 0 = no access). Access was defined to include the availability of a service in a location and its affordability for the various livestock keepers. It was hypothesized that access to services could be determined by bio-geographic and socio-economic circumstances and the types of service providers. A binary logistic regression was fitted to model the probability or likelihood of a livestock keeper under a certain bio-geographic and socio-economic condition accessing a service in reference to livestock keepers in a different bio-geographic and socio-economic condition.

Effective demand for services was evaluated through proxy variables, namely number of visits to service providers and health expenditures over a year. Differences in effective demand across the different bio-geographic and socio-economic conditions were analyzed using a generalized linear model procedure fitting a natural logarithmic transformation of the data to meet the normal distribution assumption for a linear model analysis and fitting a Poisson distribution for the count data of number of visits to service providers. In all analyses, comparisons between the likelihood of a livestock keeper under a certain socio-economic condition having more access to services or making more visits in reference to other conditions were made using odds ratios as suggested by Abeyasekera (13) and Agresti (14).

Satisfaction of livestock keepers with services provided by the different service providers was assessed based on respondents' scoring (out of 10) of four variables assumed to measure satisfaction, namely availability, quality, accessibility, and timeliness of services. Principal component analysis was conducted on the four variables to extract a single measure of satisfaction. Mean scores on the transformed variable were calculated for each bio-geographic and socio-economic categories to measure satisfaction of livestock keepers with the different service providers.

RESULTS

Health Service Value Chains

The mapping of actors involved in the provision of animal health services (**Table 2**) showed that the value chain structure is influenced by the administrative organization of the government of Ethiopia. The federal ministry of agriculture and the regional livestock bureaus are the enabling bodies in their respective domains. Thus, federal and regional policies and strategies are the key enabling instruments for improving health services.

Both the public and private sectors are involved in animal health service delivery. The private sector is mainly involved in drug sales, and that is mainly in district towns, while clinical or diagnostic services are very minimal and are available only in and around urban areas. It is estimated that private drug shops and clinics account for 75 and 25% of the private service centers, respectively. For instance, in a 2001 estimate, the number of private importers, clinics + drug shops, clinics only, animal health posts and drug shops were 127, 94, 40, 35, and 180, respectively (15).

Yet, importation and distribution of pharmaceuticals, including to the public sector, is predominantly the private sector's domain, reflecting the fact that this is likely the main domain where profits are possible. Effective delivery of animal health services is hampered by absence or under-equipped and under-staffed district laboratories, inefficient delivery of supplies, severe shortage of transportation means to deliver services, and poor quality drugs/vaccines, unethical practices both by the public and private sector practitioners, and importantly absence of favorable enabling environment for the private sector. The key public and private sector service providers identified through household surveys included livestock extension agents, public/official veterinarians and CAHWs, drug shops, traditional healers, and private veterinarians (**Figure 1**). Vaccination is primarily provided by the CAHWs (71.4% of respondents), the public veterinary service (56.9%), and extension agents (50.4%, whose role would likely be limited to awareness creation and organizing the vaccination campaigns. The private veterinary clinics provided most of the clinical services compared to the public veterinarians, the percentage of respondents claiming to get services from the private and the public sectors being 50 and 26%, respectively. The drug shops also provided clinical services including most of the deworming services, violating the limitations of their professional business license, as reported by 37.8 and 24.2% of the respondents, respectively. Advice and trainings on herd health and information on diseases is virtually absent despite its potential importance in the traditional livestock production systems. These services were mainly provided by the extension agents.

Animal Health Services

Animal health services provided in Ethiopia include vaccination, modern (clinical services by professional and paraprofessionals) and traditional treatments, GIT parasite (deworming) and external parasite (spraying/dipping) controls, disease outbreak investigations and information on diseases outbreaks, herd health advices, and trainings (**Figure 1**). The services most frequently reported by the livestock keepers were vaccination and modern treatments, being reported by 40.9 and 21.4% of the respondents, respectively. External parasite control, outbreak investigation, herd health advices, delivery of trainings and disease information are the least available services, reported by 0.2 to 4.0% of the respondents.

Services provided were similar across the three major livestock production systems in Ethiopia, though the proportion of respondents reporting the different services varied significantly across the systems (**Table 3**). Availability of vaccination and traditional treatment services were reported by a larger proportion of the respondents in pastoral and agropastoral systems ($P < 0.05$). Advice on herd health management, trainings and information on disease outbreaks were more available in mixed crop-livestock system ($P < 0.05$).

Access to Services

Multinomial logistic regression analyses showed that biogeographic, socioeconomic, and institutional factors determined access to animal health services (**Table 4**). Livestock keepers in crop-livestock and agropastoral systems had 5.5 (odds ratio = 5.453, $P = 0.000$) and 2.5 (odds ratio = 2.482, $P = 0.000$)

TABLE 2 | Value chain analysis of animal health service delivery (actors and roles) in Ethiopia.

Actors	Location	Sector	Education	Presence	Role (secondary role in parentheses)	Remark
Kebele health posts/clinics (type D)	Villages	Public	Dipl., BSc, DVM	1 for 2-3 kebeles	Vaccination; clinical services	Growing: 1 in each *kebele* in some cases
	Villages	Private	Diploma; BSc; DVM	Very few	Clinical services	Mainly at district level
Kebele drug shops	Villages	Public	Diploma; BSc; DVM	1 for 2 *kebele*	Drug sale	Part of health post
	Villages	Private	Diploma; BSc; DVM	Few (> clinics)	Drug sale (clinical services)	Illegal clinical service
CAHWs	Villages	Private	Certificate	Very few	Vaccination (clinical services)	Pastoral areas
District clinics (type C)	Towns	Public	DVM; MVSc	Every district	Coordinate vaccination; clinical services	
	Towns	Private	Diploma; BSc; DVM	Few	Clinical services	
District drug shops	Towns	Public	DVM; MVSc	Every district	Drug sale	Part of clinic
	Towns	Private	Diploma; BSc; DVM	Few	Drug sale (clinical services)	Illegal clinical service
Large-scale pharmaceutical importers/distributors	Federal Capital	Private	DVM; MVSc	Few	Distribution to regional bureaus, private whole sealers, private shops/clinics	
Small/medium scale drug importers/distributors	Regional capitals	Private	DVM; MVSc	Few	Distribution to small clinics, drug shops	About 10-20
District laboratories	District towns	Public	DVM; MVSc	Few	Minor diagnosis	
Regional laboratories	Regional/zonal capitals	Public	MVSc; PhD	1-2 per region	investigation, surveillance, food safety, capacity building	Developing regions?
National Veterinary Institute		Public	MVSc; PhD	One	Vaccine production	High contribution
Federal laboratories (National Animal Health Diagnostic and Investigation Center)		Public	MVSc; PhD	1	Diagnostics; surveillance, food safety, capacity development	
VDFACA (Veterinary Drugs and Feed Accreditation and certification Authoriy)		Public	DVM; MVSc		Quality control	Ill-equipped; weak regional branch
Abattoirs	Regional/zonal capitals	Public	DVM; MVSc		Meat inspection	
Federal Livestock Ministry		Public	DVM; MVSc		Enablers; regulators, certification	
Regional Livestock Bureaus[a]		Public	DVM; MVSc	1/region	Enablers; regulators, certification	
Livestock keepers		Priavte	0-12 grade		Passive surveillance	Few graduates
Livestock extension agents	At all level	Public	Diploma, BSc, MSc		Livestock production advisory, coordinating/facilitating health services (esp. vaccination)	
Prof. associations, Univ., Research[b]	Federal, regional	Public	DVM; MVSc; PhD	Quite a few	Technical support	Minimal contribution

[a]Zonal, district and kebele structures. [b]Federal, regional, and international research institutes.

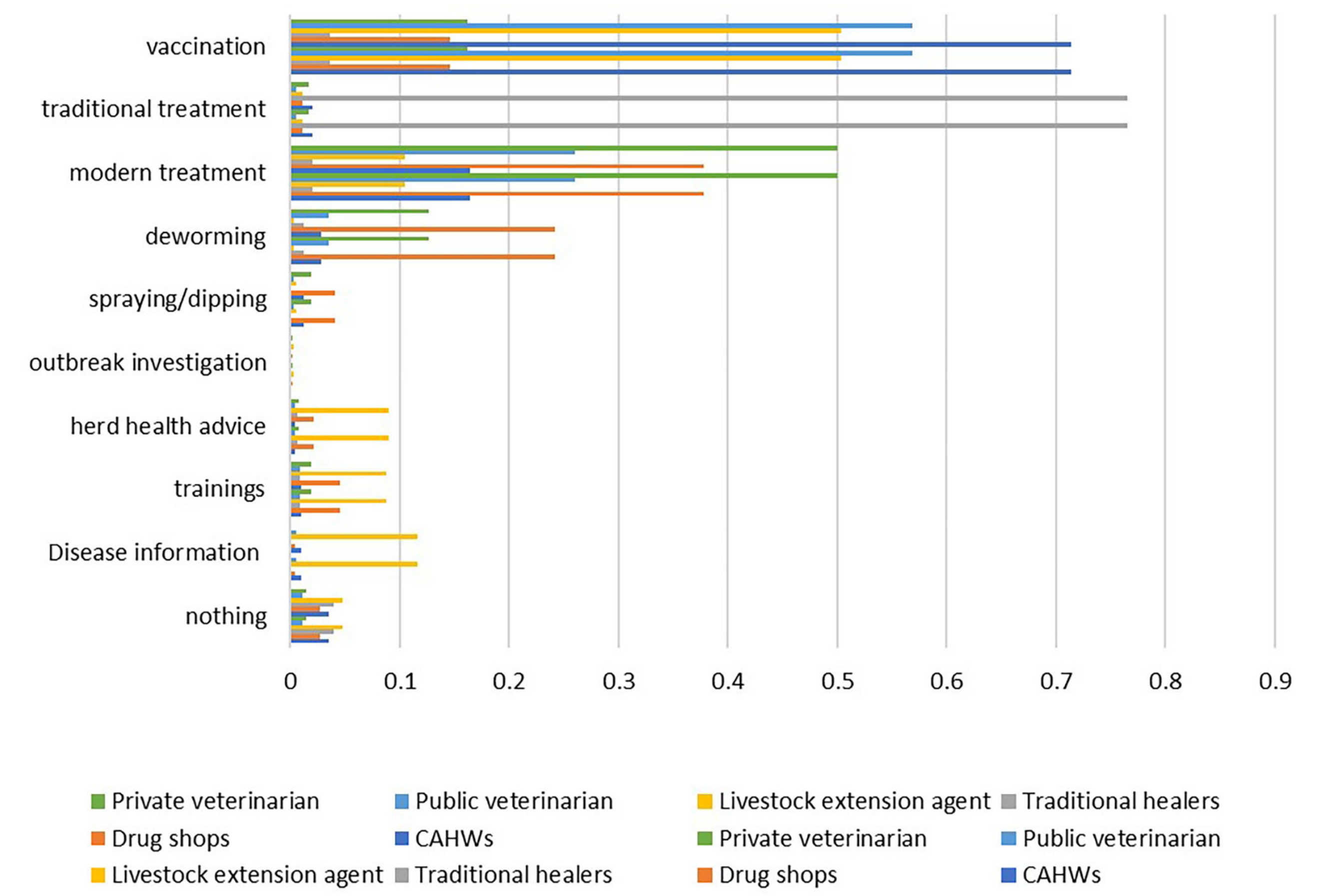

FIGURE 1 | Percentage of respondents reporting animal health service providers and their primary services in Ethiopia (CAHWs, community-based animal health workers).

TABLE 3 | Percentage of respondents reporting the primary health services provided within pastoral, agropastoral and mixed crop-livestock systems in Ethiopia.

	Crop-livestock	Agropastoral	Pastoral
Vaccination	33.8%a	50.1%b	43.2%c
Traditional treatment	5.8%a	11.1%b	12.2%b
Modern treatment[a]	22.6%a	21.1%a, b	19.5%b
Deworming	6.9%a	5.1%b	8.3%a
Spraying/dipping	1.2%a	1.1%a	1.6%a
Outbreak investigation	0.2%a	0.1%a	0.2%a
Herd health advice	5.4%a	1.2%b	1.7%b
Trainings	5.2%a	4.0%a	1.8%b
Disease information	5.5%a	1.4%b	3.0%c
Nothing	2.9%a	3.1%a	3.5%a
Other services	10.5%a	1.6%b	5.1%c

Each subscript letter denotes a subset of system categories whose column proportions do not differ significantly from each other at the 0.05 level. Modern treatment refers to clinical services provided by professionals and paraprofessionals.

times more access to services in reference to the pastoral system. Within production systems, administrative regions located in the central part of the country and/or with developed infrastructure had significantly more access to services than peripheral regions. For instance, livestock keepers in Amhara and Oromia regions located in the central part of the country in crop-livestock system and in Oromia region in agropastoral and pastoral systems reported better access to services than the reference regions which are located in the border area or have less developed infrastructures (**Table 4**).

Determinants of access to animal health services were similar across the three livestock systems studied (**Table 5**). Male, older and wealthier livestock keepers had a higher chance of access to animal health services. However, there was no gender difference in the pastoral system and medium-aged farmers had higher access to services than older in crop-livestock system.

In reference to private veterinary clinics, livestock keepers reported higher access to services provided by all the other service providers, particularly to services provided by extension agents, drug shops, and CAHWs. Similarly, male headed households and

TABLE 4 | Biogeographic, socioeconomic, and institutional determinants of access to animal health services in Ethiopia.

Parameter	*B*	SE	Sig (*P*)	Exp(B)[a]
Intercept	−4.212	0.118	0.00	0.015
System = Crop-livestock	1.696	0.128	0.00	5.453
System = Agropastoral	0.909	0.186	0.00	2.482
System = Pastoral	0[b]	.	.	1
Region = Amhara (system = crop-livestock)	0.510	0.096	0.000	1.665
Region = Oromia (system = crop-livestock)	0.229	0.095	0.016	1.257
Region = SNNP (system = crop-livestock)	−0.205	0.108	0.057	0.815
Region = Tigray (system = crop-livestock)	0[b]	.	.	1
Region = Afar (system = Agropastoral)	−0.731	0.208	0.00	0.482
Region = Oromia (system = Agropastoral)	0.950	0.167	0.00	2.585
Region = SNNP (system = Agropastoral)	0.145	0.171	0.39	1.156
Region = Somali (system = Agropastoral)	−1.025	0.216	0.00	0.359
Region = Benishangul (system = Agropastoral)	0.747	0.189	0.00	2.11
Region = Gambella (system = Agropastoral)	0[b]	.	.	1
Region = Afar (system = Pastoral)	0.131	0.111	0.238	1.14
Region = Oromia (system = Pastoral)	2.004	0.097	0.00	7.418
Region = SNNP (system = Pastoral)	0.846	0.114	0.00	2.331
Region = Somali (system = Pastoral)	0[b]	.	.	1
Male HH head	0.094	0.042	0.025	1.098
Female HH head	0[b]	.	.	1
Herd size				
Medium (10.5)	0.425	0.044	0.00	1.53
Large (25.7)	0.542	0.049	0.00	1.72
Very large (99.8)	0.693	0.057	0.00	1.999
Small (2.8)	0[b]	.	.	1
HH age category (average)				
1st quartile (29.9)	−0.041	0.043	0.343	0.96
2nd quartile (39.4)	0.061	0.046	0.180	1.063
3rd quartile (47.0)	0.069	0.044	0.117	1.072
4th quartile (61.4)	0[b]	.	.	1
Service providers				
CAHWs	1.143	0.063	0.00	3.136
Drug shop	1.396	0.062	0.00	4.04
Traditional healer	0.492	0.067	0.00	1.636
Extension agent	2.077	0.061	0.00	7.978
Public vets	1.535	0.062	0.00	4.642
Private vets	0[b]	.	.	1

[a] *(Exp(B): the odds of reporting access to service in reference to no access).*
[b] *Set to zero because this parameter is redundant as it is the reference category.*

wealthier livestock keepers (measured by their herd sizes) had more access to services. The proportions of respondents in the different system, gender, and age categories reporting access to services are presented in **Table 6**.

Effective Demand for Services

Effective demand for services was evaluated through two proxy variables, namely number of visits to service providers and health expenditures over a year. All the determinants evaluated (**Table 6**) significantly determined the number of visits a livestock keeper made to service providers. Highland crop-livestock farmers used the services provided more often than pastoralists (odds ratio = 2.93; P = 0.000), but the difference between pastoralists and agropastoralists was not significant (odds ratio = 1.025; P = 0.228). The average number of visits made by a crop-livestock farmer, agropastoralist and pastoralist in the year preceding the surveys were 11.1, 3.0, and 3.3, respectively. Pastoralists, however, paid significantly more per service/visit (USD 3.05) than both crop-livestock farmers (USD 1.38) and agropastoralist (USD 2.36) (**Table 7**).

While the frequency of visits to the private veterinary clinics was significantly lower than to the other service

TABLE 5 | Biogeographic, socioeconomic, and institutional determinants of access to animal health services in mixed crop-livestock, agropastoral and pastoral livestock production systems in Ethiopia.

	Crop-livestock system				Agropastoral system				Pastoral system			
Parameter	***B***	**SE**	**Sig (*P*)**	**Exp(B)[b]**	***B***	**SE**	**Sig (*P*)**	**Exp(B)[b]**	***B***	**SE**	**Sig (*P*)**	**Exp(B)[b]**
Intercept	−2.009	0.0900	0.000	0.134	−3.366	0.1829	0.000	0.035	−3.225	0.1982	0.000	0.040
Male HH head	0.119	0.0566	0.036	1.126	0.259	0.1082	0.017	1.295	−0.030	0.0787	0.706	0.971
Female HH head	0[a]			1	0[a]			1	0[a]			1
Herd size												
Medium (10.5)	0.647	0.0562	0.000	1.910	0.299	0.0861	0.001	1.349	0.473	0.1544	0.002	1.604
Large (25.7)	0.982	0.0709	0.000	2.669	0.388	0.0788	0.000	1.474	0.408	0.1422	0.004	1.503
Very large (99.8)	1.054	0.1616	0.000	2.870	0.259	0.0853	0.002	1.296	0.365	0.1361	0.007	1.440
Small (2.8)	0[a]			1	0[a]			1	0[a]			1
HH head age category (average age)												
1st quartile (29.9)	0.063	0.0697	0.367	1.065	−0.209	0.0751	0.005	0.811	−0.197	0.0774	0.011	0.821
2nd quartile (39.4)	0.050	0.0703	0.475	1.052	−0.074	0.0849	0.383	0.929	−0.115	0.0847	0.173	0.891
3rd quartile (47.0)	0.194	0.0666	0.004	1.214	−0.249	0.0822	0.002	0.780	−0.030	0.0843	0.726	0.971
4th quartile (61.4)	0[a]			1	0[a]			1	0[a]			1
Service providers												
CAHWs	−0.678	0.1013	0.000	0.508	2.178	0.1447	0.000	8.833	2.577	0.1423	0.000	13.160
Drug shop	0.664	0.0835	0.000	1.943	2.233	0.1444	0.000	9.330	2.041	0.1444	0.000	7.696
Traditional healer	−0.401	0.0956	0.000	0.670	1.531	0.1496	0.000	4.625	1.276	0.1516	0.000	3.581
Extension agent	2.213	0.0842	0.000	9.140	2.443	0.1436	0.000	11.506	1.917	0.1452	0.000	6.798
Public vets	1.410	0.0816	0.000	4.095	2.182	0.1447	0.000	8.865	1.380	0.1502	0.000	3.975
Private vets	0[a]			1					0[a]			1

[a]*Set to zero because this parameter is redundant as it is the reference category;* [b]*(Exp(B): the odds of reporting access to service in reference to no access).*

TABLE 6 | Proportion (%) of male and female respondents with different age groups and herd sizes in different production systems reporting access to animal health services by different service providers in eight regions of Ethiopia.

Production systems	CAHWs	Drug shops	Traditional healers	Extension agent	Public vets	Private vets
Crop-livestock	11.5	32.5	14.6	68.0	49.6	20.2
Pastoral	40.1	28.2	15.5	25.7	16.9	4.9
Agropastoral	30.3	31.4	18.6	36.1	30.3	4.7
Gender of HH head						
Female	24.0	24.9	12.0	47.9	37.2	11.1
Male	26.6	32.1	17.0	44.5	32.8	10.6
Herd size category						
Small (2.8)	14.8	20.0	9.0	51.1	36.0	9.7
Medium (10.5)	17.5	33.1	19.1	60.3	44.2	15.9
Large (25.7)	26.1	36.6	21.5	46.9	35.6	12.4
Very large (99.8)	45.2	33.9	15.2	23.4	19.4	5.2
Age category (average)						
1st quartile (29.9)	26.3	28.9	16.6	39.8	30.5	8.6
2nd quartile (39.4)	24.6	30.5	17.6	46.5	34.1	10.3
3rd quartile (47.0)	28.2	31.9	14.3	48.4	34.6	12.0
4th quartile (61.4)	25.0	32.5	16.0	47.5	36.1	12.4

providers (**Table 6**), the average service fee per service was reported to be significantly higher (**Table 7**). The average number of visits and service fees ranged from 1.8 and USD 3.77 for the private veterinarian to 19.2 and USD 0.61 to livestock extension agents. Female livestock keepers made more visits compared to males (9.2 vs. 6.5) but paid significantly

TABLE 7 | The odds of [Exp(B)] a livestock keeper from the different livestock systems, gender and age categories and service providers reporting a higher number of visits in reference to those in the reference category within each parameter.

Parameter	β	SE	Sig (*P*)	Exp(β)
Intercept	0.041	0.0388	0.296	1.041
System = Crop-livestock	1.074	0.0182	0.000	2.928
System = Agropastoral	0.024	0.0201	0.228	1.025
System = Pastoral	0[a]	.	.	1
Male HH head	−0.028	0.0109	0.011	0.973
Female HH head	0[a]	.	.	1
Herd size				
Medium (10.5)	−0.126	0.0106	0.000	0.882
Large (25.7)	−0.676	0.0147	0.000	0.509
Very large (99.8)	−0.034	0.0183	0.062	0.966
Small (2.8)	0a	.	.	1
Age of HH head (average)				
1st quartile (29.9)	−0.22	0.0128	0.000	0.803
2nd quartile (39.4)	−0.195	0.0132	0.000	0.822
3rd quartile (47.0)	−0.016	0.012	0.191	0.984
4th quartile (61.4)	0[a]	.	.	1
CAHWs	0.352	0.039	0.000	1.422
Drug shop	0.758	0.0354	0.000	2.133
Traditional healer	0.54	0.0414	0.000	1.716
Extension agent	2.482	0.032	0.000	11.971
Public vets	0.498	0.0354	0.000	1.646
Private vets	0[a]	.	.	1

[a] *Set to zero because this parameter is redundant.*

less (USD 1.18 vs. 2.27). Small livestock keepers visited health centers more frequently but paid the least amount (**Table 8**).

Satisfaction With Services

Satisfaction of livestock keepers with services was evaluated based on four measures, namely availability (av), accessibility (ac), quality (qw), and timeliness (tm) of services. The average scores (out of 10) for av, ac, qw and tm were 6.1, 5.9, 6.2, and 5.7, respectively. Principal component analysis, conducted to derive a latent variable "satisfaction" from the four measures, extracted only one factor, indicating the four variables are measuring the same construct (satisfaction). Regressing the latent variable satisfaction on the four measures gave significant ($P = 0.000$) b-values of 0.22, 0.20, 0.13, and 0.14 for av, ac, qw, and tm, respectively, indicating strong relationships between the latent variable satisfaction and its measures.

Based on the first factor extracted, livestock keepers are most satisfied with the private veterinary clinics with the highest score of 0.22, followed by the public veterinary service and traditional healers with scores of 0.083 and 0.067, respectively. The private veterinarians provided the most satisfactory service across all livestock production systems and for all socio-economic groups, except for livestock keepers with very large herds (**Figure 2**).

DISCUSSION

Improved livestock productivity is largely a function of high-quality, efficient and sustainable provision as well as strong governance of veterinary services. Veterinary services, in turn, are influenced by a multitude of determinants/factors stemming from the farmers behavior toward the demanded veterinary services. The present study revealed that animal health services in the various livestock production systems of Ethiopia remain far below satisfactory standards, in line with the OIE assessment of the PVS (16) of the livestock sector (17) and animal health situation analysis of the country (5). In general, the performance of the animal health services in Ethiopia could be categorized unsatisfactory in reference to OIE's four evaluation pillars (16), including the absence of continued professional development program (CPD) and public-private partnership (PPP) for delivery of animal health services, although initiatives are underway to develop CPD program and PPP models (18).

Veterinary Services and Service Providers

The survey findings indicated that the veterinary services provided to livestock keepers encompass disease control approaches (including modern clinical services and traditional healings) and preventive measures (vaccination), with little emphases given to parasite/pest control, disease outbreak investigation/information management, awareness/advises and

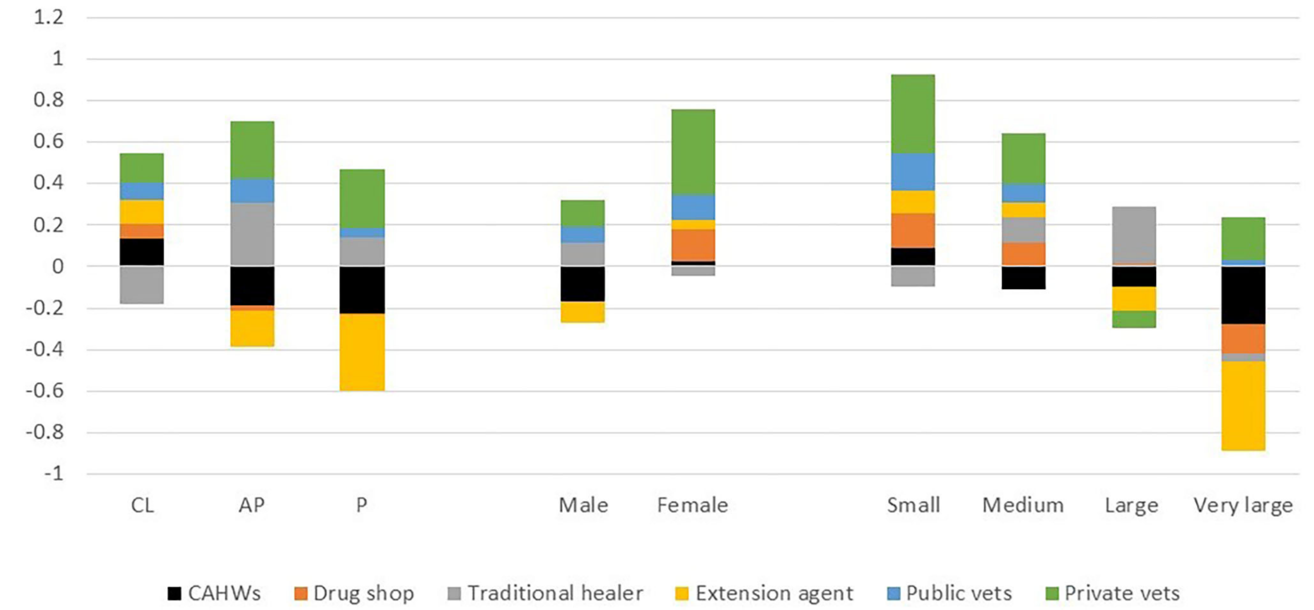

FIGURE 2 | Satisfaction scores allocated by male and female respondents keeping small, medium, large and very large herds in crop-livestock (CL), agropastoral (AP), and pastoral (P) systems for services provided by different service providers in Ethiopia (scores presented are based on the first principal component factor).

TABLE 8 | The odds of [Exp(B)] a livestock keeper from the different livestock systems, gender and age categories and using the different service providers expending a higher amount of money in reference to those in the reference category within each parameter.

Parameter	*B*	SE	Sig (*P*)	Exp(*B*)
Intercept	4.56	0.16	0.00	95.66
System = Crop-livestock	−0.39	0.07	0.00	0.68
System = Agropastoral	−0.17	0.05	0.00	0.84
System = Pastoral	0[a]	.	.	1.00
Male HH head	0.40	0.09	0.00	1.49
Female HH head	0[a]	.	.	1.00
Herd size				
Medium (10.5)	−0.13	0.01	0.00	0.88
Large (25.7)	−0.68	0.01	0.00	0.51
Very large (99.8)	−0.03	0.02	0.06	0.97
Small (2.8)	0[a]	.	.	1.00
HH age category (average)				
1st quartile (29.9)	−0.03	0.06	0.64	0.97
2nd quartile (39.4)	0.02	0.06	0.77	1.02
3rd quartile (47.0)	0.06	0.05	0.31	1.06
4th quartile (61.4)	0[a]	.	.	1.00
CAHWs	−1.53	0.14	0.00	0.22
Drug shop	0.12	0.06	0.06	1.12
Traditional healer	−2.10	0.31	0.00	0.12
Extension agent	−1.82	0.15	0.00	0.16
Public vets	−0.87	0.09	0.00	0.42
Private vets	0[a]	.	.	1.00

training specially to the pastoral and agro-pastoral livestock rearing communities about herd health. This is in contrast to priorities reported by livestock keepers.

There is ample information disclosing critical gaps of the veterinary services in Sub-Saharan (SS) and the Greater Horn of Africa (GHA), especially with regards to the investigation, reporting, management and rapid response to livestock disease outbreaks (7, 19–21). In Ethiopia, livestock disease surveillance and reporting is not only poor but very irregular, with only 30–35% of administrative zones submitting monthly disease outbreak reports (5, 9). The situation is worse for pastoral and agro-pastoral areas (below 5%) where the sensitivity, specificity and timeliness of the reports are very low (5). Therefore, in view of the Ethiopian Livestock Master Plan there is a need to establish a robust animal health information system by improving the quantity and quality of disease outbreak and inspection reports, and conducting risk-based active surveillance on selected Transboundary animal diseases (TADs).

The present survey essentially identified major determinants governing the delivery of veterinary services, including accessibility, type of service providers, effective demand and satisfaction by livestock keepers, among others. It is widely accepted that the delivery of quality veterinary services within specific agro-ecology/production system is influenced by several factors, including farmers' perceptions toward the services, wealth status and education level of the household heads, among others (22–25).

The current study highlighted the vital role of private service providers (including CAHWs and private vets/paravets) in the veterinary service provision. Under effective training and close monitoring, CAHWs have been one of the most effective development agents to deliver house-to-house clinical services, vaccination services, control of parasites (deworming and spraying), as well as disease outbreak investigation and reporting particularly in the remote, marginal areas of the pastoral regions of Ethiopia (5, 15, 26). Even more so, their training needs to be carefully looked after to ensure that services provided are of quality and fulfill their purpose.

However, this survey clearly disclosed the little attention given to mitigating the effects of major GIT and ecto-parasites in the respective bio-geographic zones. This is in agreement other research findings in the Ethiopian highlands (23, 27–29), as well as agro-pastoral and pastoral agro-ecologies (5, 30) where the impacts of infectious and parasitic diseases on the livestock sub-sector remain high to the present date. In consequence, the national leather industry has been seriously damaged due to poor quality of skin and hide. For this reason, it is compulsory to strengthen grassroots-level animal health extension services to control/prevent the spread and deleterious effects of parasitic diseases, through the identification of areas of risk, the preparation of animal health knowledge kit, and sharing of good practices among the farming communities.

Similarly, veterinary drug shops were exposed providing unlicensed clinical services, as reported by nearly 40% of the respondents. This is an illegal act and serious violation of the existing Ethiopian regulations, which strictly prohibit private pharmacy entities to deliver clinical services whatsoever. It is not unusual to witness the private veterinary pharmacies/drug venders, in remote rural areas, engaging in drug smuggling, providing a mix of veterinary products and herbicides/pesticides, insecticides, and even medical formulations. There are increasing evidences of the misuses of drugs among the various actors including veterinary and public health, which has strongly contributed to the worsening of Anti-microbial Resistance in the field (31–33). It implies that pertinent veterinary authorities should implement strong monitoring strategies of public regulations especially at the grassroots level.

Access to Veterinary Services

Generally, accessibility, availability and affordability of veterinary services and goods are inherent parameters which determine the quality of animal health care systems. Yet, this household survey revealed that the coverage and access of livestock keepers to veterinary services substantially varied across livestock systems, though access is relatively better in the crop-livestock systems in reference to the lowlands. This is to be expected as the available information indicates the relative concentration of the national veterinary personnel and basic infrastructure along with other logistics in the crop-livestock system mainly found in the densely populated central highlands of the country (5, 9). Moreover, livestock owners in these areas are better-off in terms of access to improved extension systems, credit/saving and other inputs services (1, 5, 27, 28). Research findings in other countries in East, West, Central and South Africa, and Asia have also revealed the strong differences in farmers' access to animal health services across different agro-ecological zones and production systems (19–22, 25, 34). These findings may also indicate that the way animal health systems are defined with sedentary livestock production systems and thus likely fail to address needs of more mobile pastoralist communities.

Indeed, the study has found that better access was reported in crop livestock and services are found to be least accessible to pastoral production systems. One of the reasons for poor access to veterinary services in pastoral areas is due to the fact that veterinary services in the pastoral areas are being delivered according to extension packages tested in sedentary production systems (i.e., crop-livestock system) and have therefore proved to be impractical and unsustainable (35). The other reason for the poor access to veterinary services in pastoral areas is due to mobility of the pastoralists, its remoteness and poor infrastructure that denies employment of professionals in arid, remote and marginal pastoral areas. Budget limitations, underdeveloped infrastructures and weak institutional arrangement are some of the problems associated with poor access to veterinary services in pastoral areas of the country.

According to this study, delivery of veterinary services in the remote and marginal lowlands of Ethiopia has been facing severe challenges in accessing affordable and reliable veterinary services (an average of only 19.3%). There are concrete reports and research findings indicating the fact that delivery of animal health services in marginalized areas have been hampered by a multitude of challenges including lack of resources by government and the low incentives for setting up private practices (7, 26, 30, 34, 36). In view of helping these communities out of chronic poverty, and realizing the national Livestock Master Plan, there is an urgent, need for commitment to enhance veterinary services in pastoral areas through accredited, nationally harmonized, and transparent community-based animal health system linked with veterinary support, involving the coordination of all agencies operating in the sector, including private service providers.

The business environment, including the highly subsidized service by the public sector, does not seem to encourage the private sector to participate, particularly in remote pastoral areas. Although the policy basis has been laid, including the "Public Private Partnership Proclamation No. 1076/2018" issued on the 22 February 2018, the "Animal Diseases Prevention and Control Proclamation No. 267/2002" and the Veterinary Services Rationalization Road Map in 2014, there has not been much progress in developing favorable legislative framework to promote participation of the private sector and the road map is yet to be ratified by the Government of Ethiopia.

Effective Demand and Satisfaction With Services

Persistent farmers' demand for veterinary services among alternative providers is governed by accessibility, availability, quality, affordability, and timeliness of the services. The survey revealed livestock keepers (regardless of demographic attributes, animal herd size, etc.) more frequently visiting public veterinary entities than the private counterparts. This can be explained mainly in terms of the limiting national livestock policy in which, which until recently, considered veterinary services as public goods, providing little incentives to farmers to seek private services This can imply the policy favoring high subsidies or even exempting service charges which could be a driving factor to attract the community to seek public services and prevent private sector actors to enter the market. Despite considerable improvements in food security and household income over the last decade, this government scheme has highly contributed to build dependency syndrome among the community in relation to veterinary services.

Yet, there are promising government commitments to expand the private engagement in veterinary services delivery. A consultative study conducted by EVA through the EU-funded LVC/PPD project has shown incremental roles of the private sector in the veterinary domain (37), supporting the above. There are also other research findings which point the opportunities attracting farmers toward livestock rearing, including availability of reliable veterinary services, market access, extension services, etc. (5, 20, 21, 23, 27).

Supporting this push toward private sector involvement, are the findings of the multinomial regression analysis in this study, which singled out private veterinary clinics as the most satisfactory service providers for the majority of livestock keepers in all the livestock production systems, despite the highest service charges. This can be explained in relation to the frequent absence of vet supplies in most government entities as the result of budgetary constraints, negligence and recurrent turnover of veterinary personnel, and public bureaucratic issues along the supply chain. On the other hand, private veterinary service providers spend most of their time on-duties, in view of maximizing their profits and expanding their enterprises. The shortage of veterinary supplies is more severe in remote pastoral areas which results in higher cost of services as shown in the higher expenditure of pastoralists in the current study.

SUMMARY AND CONCLUSIONS

In summary, the present study identified access to better veterinary services and types of providers, effective demand and satisfaction of the livestock keepers as the major determinants of veterinary service delivery in various livestock systems of Ethiopia. In the absence of well-documented information about these factors, this survey will undoubtedly act as the milestone for the national efforts to implement and enhance the livestock master plan in view maximizing the economic outputs from the huge livestock sub-sector. With active government policy support, livestock sector will radically transform (with moderate to high level of intensification) to respond to the increasing demands in Ethiopia. In this regard, the present study would contribute to the efforts for rationalization of veterinary service delivery. In the face of multitude opportunities, challenges and uncertainties, there is a need to expand the role of private veterinary services, with the public actor eventually capitalizing its roles mainly on regulatory and capacity building issues.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The data will be availed upon reasonable request and in consultation of the stakeholder institutions participating in the study. Requests to access these datasets should be directed to s.gizaw@cgiar.org.

AUTHOR CONTRIBUTIONS

BW and BG designed and led the surveys. MW, SG, and HA coordinated/collected the data. GG sourced funds and coordinated surveys (excluding HEARD project survey). BW initiated and designed the concept for the paper. SG analyzed the data. SG and BW drafted the paper. FA and GA drafted introduction and discussion sections. All authors read, commented, and approved the final manuscript.

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Livestock Network Analysis for Rhodesiense Human African Trypanosomiasis Control in Uganda

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Background: Infected cattle sourced from districts with established foci for *Trypanosoma brucei rhodesiense* human African trypanosomiasis (rHAT) migrating to previously unaffected districts, have resulted in a significant expansion of the disease in Uganda. This study explores livestock movement data to describe cattle trade network topology and assess the effects of disease control interventions on the transmission of rHAT infectiousness.

Methods: Network analysis was used to generate a cattle trade network with livestock data which was collected from cattle traders ($n = 197$) and validated using random graph methods. Additionally, the cattle trade network was combined with a susceptible, infected, recovered (*SIR*) compartmental model to simulate spread of rHAT (R_o 1.287), hence regarded as "slow" pathogen, and evaluate the effects of disease interventions.

Results: The cattle trade network exhibited a low clustering coefficient (0.5) with most cattle markets being weakly connected and a few being highly connected. Also, analysis of the cattle movement data revealed a core group comprising of cattle markets from both eastern (rHAT endemic) and northwest regions (rHAT unaffected area). Presence of a core group may result in rHAT spread to unaffected districts and occurrence of super spreader cattle market or markets in case of an outbreak. The key cattle markets that may be targeted for routine rHAT surveillance and control included Namutumba, Soroti, and Molo, all of which were in southeast Uganda. Using effective trypanosomiasis such as integrated cattle injection with trypanocides and spraying can sufficiently slow the spread of rHAT in the network.

Conclusion: Cattle trade network analysis indicated a pathway along which *T. b. rhodesiense* could spread northward from eastern Uganda. Targeted *T. b. rhodesiense* surveillance and control in eastern Uganda, through enhanced public–private partnerships, would serve to limit its spread.

Keywords: HAT, cattle market, network analysis, livestock trade, risk, Uganda

INTRODUCTION

Animal movements are integral to livestock trade but are not without risk for disease transmission. Infected Indian cattle in transit to Brazil reintroduced rinderpest to Europe in 1920, an infection that was eradicated worldwide in 2011 (1). The Office International des Epizooties (OIE) was established to mitigate risk and combat animal diseases (including zoonoses) at global level (1). The most infectious diseases for humans which are zoonotic in origin only serve to exacerbate risk for humans and animals (2), complicating trade and biosecurity within and between countries. Considerable efforts are put in place, underpinned by government policy to prevent disease spread, including attempts to develop a One Health approach to protect animal and human health (3). However, despite best efforts, these may be insufficient as evidenced by migration of Africa Rift Valley fever to Madagascar (4) and the struggle faced by Uganda over two decades to halt migration of *T. b. rhodesiense* HAT (rHAT) (5). Public–private partnerships were used to prevent impeding epidemic and spread of rHAT in eastern Uganda (6).

Since 2001, movements of infected animals from districts for which rHAT is endemic to new unaffected districts have spread rHAT around the shores of Lake Kyoga, toward the *T. b. gambiense* HAT (gHAT) focus in the north of the country (7–10). In 2008, 40% of cattle involved in inter-district trade were estimated to have been transported from rHAT endemic zones in the southeast to north and central districts (11).

Close examination of livestock movements and market networks offers the opportunity for understanding risk and exploring potential pathogen transmission. Trade is complex and dynamic and can be interrogated using complex network analysis (12–14); can accommodate bidirectional relations such as animal movement, trade, and contacts (15); and provides a theoretical framework for analysis of network properties and comparisons (16–18).

Contact network analysis has been used for modeling disease spread and to predict epidemics (19–21). Social network analysis (SNA) has been used to establish sexual contact relationships for human immunodeficiency virus/acquired immunodeficiency syndrome (22, 23) and has proved useful for studies of infectious disease transmission in livestock and wildlife. Studies include determining spread of tuberculosis in cattle (24) and in brushtail possums (25); *Escherichia coli* O157 in cattle (26); avian influenza in poultry (27, 28); and Foot and Mouth Disease in the UK (29–37). Livestock trade networks have been previously explored using SNA (38–40), particularly in Africa and in studies linking livestock trade to risk of zoonotic disease spread (41, 42).

This study explores cattle trade dynamics in eastern and northern Uganda regions to (1) understand cattle trade network topology and (2) evaluate the effects of disease control interventions on the spread of rHAT with varying infectiousness. Specifically, the study aimed to determine the role of the inter- and intra-district cattle trade in the potential spread of rHAT and identify key cattle markets for targeted disease surveillance and control.

METHOD

Study Site

This study was conducted in SE Uganda in Tororo and Namutumba districts. Vegetation cover in the area is mainly composed of savannah grassland interspersed with *Lantana camara* shrubs (43–45). The study area receives 1,200–1,500 mm of rainfall annually, which is bimodal in distribution. There are two wet seasons (March–May and September–November) and two dry seasons (December–February and June–August) (43). The daily mean minimum temperature is 15.8°C, and the mean maximum is 27.8°C (44). Agricultural economic activity comprises smallholder mixed farming, with over 80% of the population deriving their livelihood from agriculture (43) producing several different food and cash crops and integrating crop production with livestock keeping revised (46). The main reason for keeping cattle is as draft for crop cultivation; work oxen represent 36.5–43.7% of the cattle population (47, 48). Movement of untreated cattle is common in SE Uganda (49). A spatial study showed that predicted spread of endemic vector-borne and parasitic bovine infectious diseases common in these districts includes animal African trypanosomiasis (AAT), theileriosis (East Coast fever), babesiosis, anaplasmosis, heartwater, gastroenteritis, and fascioliasis (50, 51).

Tororo and Namutumba districts have been endemic for rHAT since the late 1980s (52) with human infective parasites identified in indigenous cattle in Tororo district since 1987 (53–58). *T b. rhodesiense* HAT has spread around the shores of Lake Kyoga causing significant human outbreaks associated with movement of infected animals (7, 9, 59) driven by a policy of restocking to assist districts further north, impoverished by war and generations of cattle raiding by the Karamajong in the 1980s and 1990s (11). Cattle raiding by the Karamajong depleted the livestock population in some areas to 3% of their original size (60), although not all districts in eastern and northern Uganda; these regions have similar agro-ecological zones, i.e., semiarid with subsistence farming of cattle, cassava, and millet (61). In Uganda, livestock traders move between districts and are not based within a specific district, thus providing a useful proxy for understanding cattle movement in most regions of Uganda.

Sampling and Data Collection

Authorized governmental livestock trade (small and large scale) takes place at defined market locations. These are local within districts and operate periodically under the jurisdiction of the local district livestock movement inspectors. All live livestock markets included in this study were identified from the records available at the district veterinary office. Livestock markets were visited on their respective market days and market transaction reports collected. Market transaction reports contained names of the trader and number of animals sold, but information on origin and destination was inconsistent. Therefore, information on animal movement was sought from cattle traders. Data was collected both directly (visiting the livestock markets in Tororo and Namutumba districts) and indirectly (livestock markets from other districts which were not visited but mentioned by the cattle

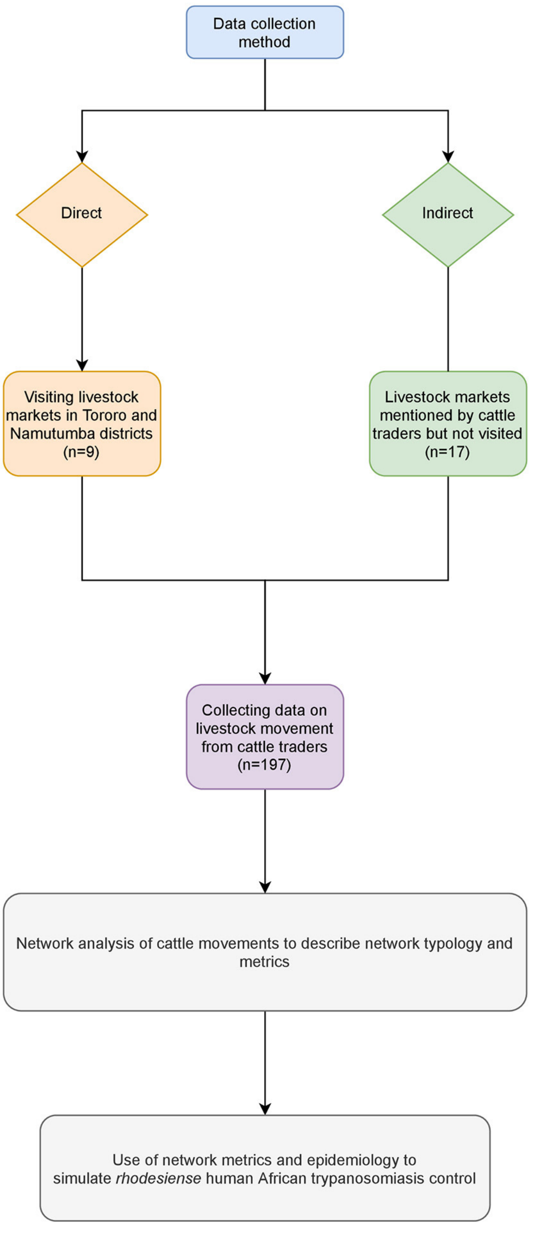

FIGURE 1 | Cattle movement data collection and analysis methods.

traders). **Figure 1** shows the flow of data collection. The livestock markets where data was directly collected are shown in **Figure 2**.

Cattle traders, through verbal consent, were interviewed using semi-structured interviews. Questionnaires were designed to capture interviewee information, livestock markets where cattle traders mostly sourced their cattle within the entire livestock trade cycle (annual), the livestock markets that these animals were sold into, and livestock market size. In total, all 197 traders present during the visit were cross-sectionally interviewed in all ($n = 9$) livestock markets in Tororo and Namutumba districts, SE Uganda. The origin and destination of the cattle as collected from this study have been provided (see **Supplementary Material**). Apart from collecting network data, we collected information on livestock market, cattle prices, and cattle trade dynamics using direct observation and conducted key informant interviews with local council authorities, cattle traders, and animal health providers.

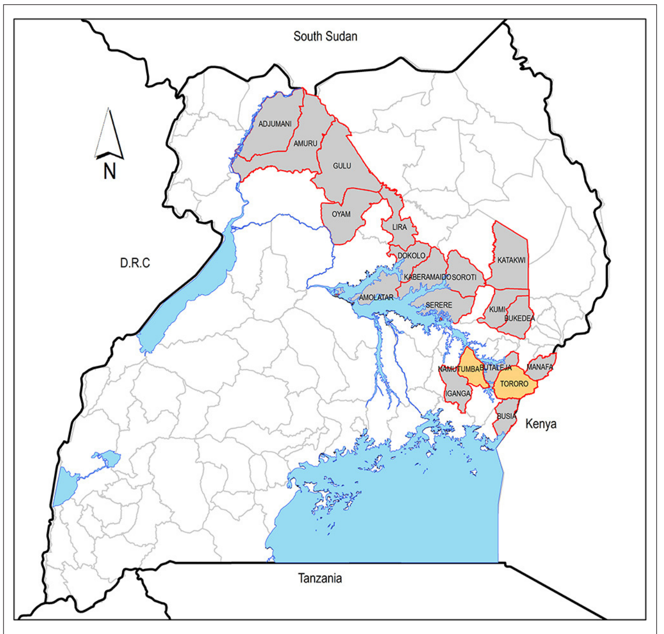

FIGURE 2 | Districts in Uganda where cattle are mostly traded. The yellow districts (Namutumba and Tororo) are where data was collected from. Water bodies are shown in blue.

Data Analysis

SNA methods of (62, 63) were applied. Cattle markets represented the nodes (or actors), and the link (or tie) was represented by the connection of cattle markets through movement of cattle. Market attributes were determined by (i) size where big markets (assigned a value of 2) were represented by >20 cattle traders with >100 cattle traded weekly; small markets (assigned a value of 1) which were represented by >20 cattle traders with <100 cattle traded weekly; and (ii) past studies (secondary data) on *T. b. rhodesiense* prevalence in livestock (11, 64, 65). Data on HAT prevalence in cattle in Uganda was obtained from searching PubMed, EBSCO, and parasitology journal databases. The obtained secondary data for *T. b. rhodesiense* prevalence was fitted *via* beta and uniform distribution and Monte Carlo simulation to obtain 95% uncertainty interval (UI) in R (package = fitdistr) (66). The total value of actor (i.e., cattle market) attribute was weighted by assigning them sizes of the cattle market and prevalence of *T. b rhodesiense* obtained from the past studies to represent strength of a cattle market (node).

The cattle trade network in Uganda was evaluated by (1) describing the network typology and (2) identifying key cattle markets (key nodes) that potentially play a major role in disease spread and hence can be a major focus for disease control based on node centrality measures. Network typology was described using inter (network level metrics) and intra (node level metrics) network metrics and community detection. Inter-network metrics analyzed included the size of the network (total number of cattle markets and contacts that make up the network), density (i.e., measuring the degree of the contacts between pairs of cattle markets in the network), clustering coefficient (i.e., measuring the average probability of individual cattle markets being directly connected to one another in the network, hence measuring the tendency of the network to cluster), and modularity (measures strength of division of a network into communities, hence used for detecting community structure in a network) using the Clauset–Newman–Moore algorithm (62, 67, 68).

Intra-network metrics analyzed included cattle market connectivity (identifying the strong component of the network), centrality (degree of centrality, degree of betweenness and degree of closeness), and cohesiveness (i.e., identifying groups of cattle markets as part of a common structure of contacts such as k-core) (69, 70). The k-core describes the maximal subgroup in which each cattle market has at least degree k. The k is a metric for determining the coreness and therefore helps identify tightly interlinked groups within a network. Community detection was done using hierarchical clustering and community membership matrices including block modeling and structural equivalence (16, 71–73) to identify communities and overlap between them. Intra- and inter-network metrics were analyzed in R (package = igraph, package = sna) (74, 75) statistical computing version 3.2.2 (76). Density was computed using the formula in (77). **Table 1** provides a summary of the network metrics including their epidemiological significance.

Cattle movement was set as directed (i.e., each cattle market has a direction associated with it) and weighted (i.e., using attributes to assign the importance of the links between cattle markets) since data obtained from livestock traders indicated the flow of cattle. Sensitivity analysis was included by setting cattle movement as undirected, i.e., cattle moving to a certain market and coming back to the original market. The study further analyzed clusters (communities) using links rather than nodes (78) within R (package = linkcomm) (79) statistical computing version 3.2.2 (76). By clustering links between the cattle markets, overlapping, and nested network structures, key cattle markets that form links across several clusters could be identified (80, 81).

Validation and Simulation of Disease Outbreak and Control

Before conducting disease spread simulation on the network, the network data was first validated using (1) Erdös-Rényi random graphs with binomial distribution and (2) small-world networks *via* random rewiring (16). Specifically, this involved

TABLE 1 | Description of network and node level metrics.

Metric	Description	Epidemiological importance
NETWORK-LEVEL METRICS		
Size	Number of cattle markets (nodes) that make up the network. It enables comparison of the Uganda cattle market with other markets' random graphs.	Larger networks may have more subgroups that act as disease transmission bottlenecks within the group
Density	Degree of contact between pairs of cattle markets in the network	Disease transmission may occur faster in high-density networks
Eigenvector centralization	Measures the level of influence of a cattle market (node) within a network after assigning each a score.	Disease transmission occurs rapidly in networks with high eigenvector centralization
Modularity	Involves partitioning of the cattle network into well-connected subgroups	Disease transmission is slowed downed by the presence of subgroups
Clustering coefficient	Is the ratio of the number of edges (i.e., links) that occur between a cattle market's (i.e., node's) immediate neighbors and the maximum number of edges that could exist between them	High clustering may increase the frequency of disease spread
NODE-LEVEL METRICS		
Degree centrality	The number of edges (links) a cattle market (node) has.	Indicates whether a cattle market can be a source of infection (high out-degree centrality) or receive most of the infection from other cattle markets (high in-degree centrality)
Degree betweenness	Measures the extent to which a cattle market (node) lies on the paths between other cattle markets	Measures how frequently a given cattle market (node) can act as a bridge between other cattle markets (nodes) in the network. The higher the degree betweenness, the higher the potential of a cattle market to transmit the infection from a source cattle market
K-core	The k-core of a graph is the maximal subgraph made of nodes with degree k or more.	Can identify superspreaders or groups within a network which are vulnerable to a disease
KEY ACTORS		
Articulation point	Is a cattle market (node) whose removal disconnects the network	Can be targeted for disease control to enhance the resilience of the network

using observed nodes to generate a random Erdös–Rényi graph and that the observed network exhibited properties of small-world effects, i.e., creation of short paths between arbitrary nodes (16). Network validation using random graphs and rewiring recommended in instances where information on the entire network is not available (82).

Using the network typology, the spread of animal disease (using rHAT as an example) was simulated in the network to assess the effects of disease control interventions on disease transmission with varying infectiousness and related probability of transmission (β). This was achieved by using a stochastic susceptible, infected, recovered (*SIR*) compartmental model. The basic reproductive number (R_o) for rHAT was obtained from previous studies (83, 84); average R_o of 1.287 was used in this study. Given that rHAT R_o was <1.5, it was used to represent a "slow" pathogen transmission. However, we also simulated a "fast" (R_o 3) disease transmission to compare with a "slow" one in the network. Probability of transmitting rHAT along the network (β) was calculated by dividing rHAT R_o with its infectious period in livestock which is on average 60 days (2 months) (84). The probability of transmission used in this study was 0.02 (1.287 divided by 60) and 30-time steps. In previous studies, it has been reported that combination of trypanocide treatment and insecticide spraying is effective, reducing rHAT transmission to R_o 0.0075 (85). Therefore, we reduced β to 0.000125 to simulate rHAT control using effective methods such as trypanocide treatment and insecticide spraying within the network. Assuming the same infectiousness period as rHAT (i.e., 60 days), we simulated disease control of a "fast" pathogen by reducing infectiousness by 50% (i.e., R_o 1.5 hence β 0.05), and a further 25% (i.e., R_o 0.75 hence β 0.0125).

RESULTS

Characteristics of Livestock Markets and Cattle Trade

Trade at the major markets is the first tier of the livestock trade chain; subsequent tiers of trading buy livestock from fellow livestock traders to sell on as live animals, for slaughter, for breeding, or for supply of animal traction. At the first tier, livestock are sold and exchanged between different livestock markets within and outside the district of the market but most often in the same region. Subsequent tiers of trade are within the district where the first-tier livestock market is found. Most livestock traders interviewed traded in livestock reported sourcing animals from within their home or adjacent districts and including districts in the Busoga/Lake Victoria crescent rHAT focus such as Iganga and Busia (**Figure 2**). The cattle markets where cattle traders traded most of their cattle were both in eastern and northern regions of Uganda. The districts in eastern Uganda where cattle were mostly traded are shown in **Figure 2**, and these included Tororo, Namutumba, Soroti, Serere, Iganga, Busia, Manafa, Butaleja, Bukedea, Kumi, Katakwi, and Kaberamaido. The northern districts (see **Figure 2**) included Dokolo, Amolatar, Lira, Oyam, Gulu, Amuru, and Adjumani. The mean selling price according to cattle type was as follows:

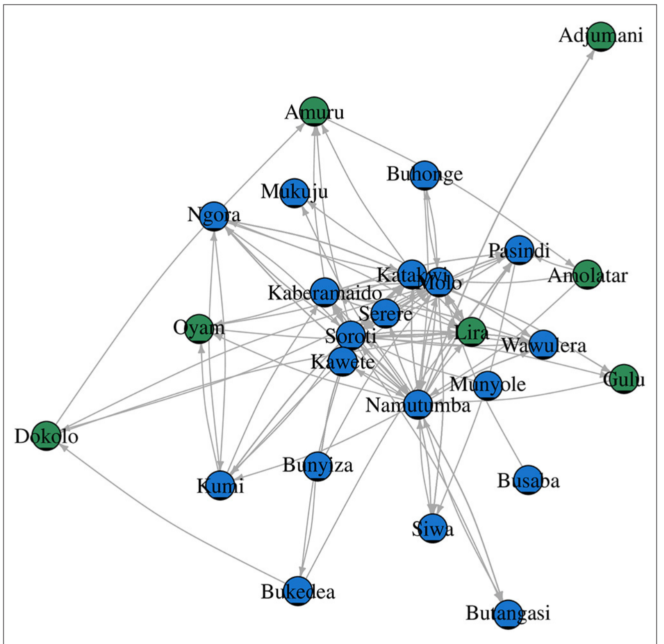

FIGURE 3 | Cattle trade network in northern (green nodes) and eastern (blue nodes) Uganda.

calves, United States dollar (USD) 37.8 (36.1–39.5), untrained young male for plowing, USD 90.3 (87.4–92.3), trained young male for plowing, USD 224.2 (182.7–267.2), cow, USD 207.7 (181.6–232.5), and adult male, USD 381 (275.8–495.2).

Network and Node Metrics

For SNA analysis, 197 traders were cross-sectionally interviewed in all ($n = 9$) livestock markets in Tororo and Namutumba districts, southeast Uganda. The cattle trade network (**Figure 3**) comprised of 26 cattle markets in both eastern and northern Uganda, 325 dyads (links between two cattle markets) and 197 links (**Table 2**) for which there were 60 mutual and 137 duplicated links. In addition, there was only one single connected component within the network. Weighted distances were also calculated to examine the length of all the shortest paths from or to the cattle markets in the network. The distance-weighted paths for the cattle markets are shown in **Figure 4**.

Grouping the cattle markets using clusters and the Clauset–Newman–Moore algorithm, network modularity was 0.1. No isolated cattle markets existed in the network. Most cattle markets were weakly connected with a few being highly connected. Overall elementary graphical indices showed the density of the graph to be 0.006; dyadic reciprocity to be 1.7; edgewise reciprocity to be 1.6; and eigenvector of centralization to be 0.3.

The degree centrality score for each cattle market is shown in **Table 3**. Soroti livestock market in SE Uganda was shown to have the highest number of links and have a centrality score of 55.0, indicating the highest movement of cattle in and out of the district, followed by adjacent livestock markets in Namutumba (54.0) and Molo (51.0). Katakwi, Lira, Pasindi, and Kaberamaido showed a moderate flow of cattle in and out of the district. Ngora,

TABLE 2 | Cattle trade network metrics in southeast and northwest Uganda.

Metric	Values	Minimum	Maximum
Number of cattle markets (nodes)	26.0	-	-
Number of links between cattle markets	197.0	-	-
Number of links between two cattle markets (dyads)	325.0	-	-
Density	0.0	-	-
Clustering coefficient	0.5	1.0	0.0
Average degree centrality	5.9	19.0	1.0
Average betweenness centrality	10.8	100.0	0.0
Average closeness centrality	0.0	-	-
Eigenvector centralization	0.3	-	-

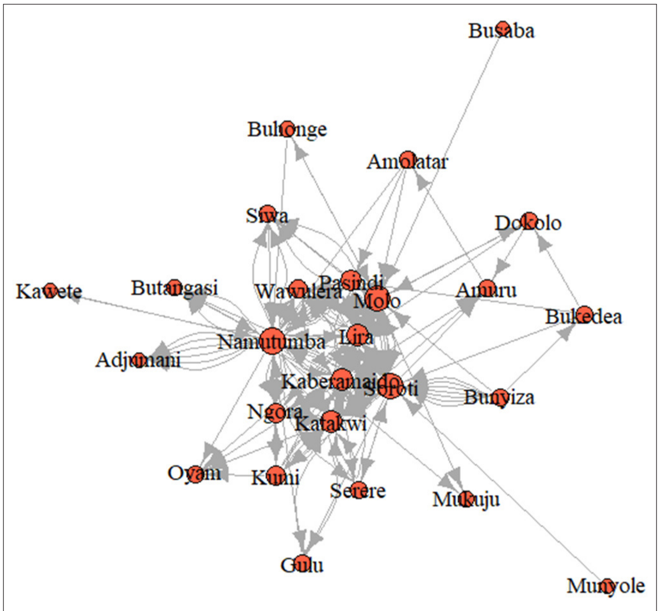

FIGURE 4 | Weighted distance paths of the cattle trade network.

TABLE 3 | Cattle trade node metrics for all markets.

Cattle market ID	Cattle market	Degree centrality	Betweenness centrality	Closeness centrality	K-cores
1	Adjumani	6	0	0	6
2	Amolatar	4	20	0	4
3	Amuru	5	21	0	4
4	Buhonge	3	0	0	3
5	Bukedea	4	0	0	4
6	Bunyiza	9	0	0	8
7	Busaba	1	0	0	1
8	Butangasi	5	0	0	5
9	Dokolo	5	0	0	4
10	Gulu	8	2	0	8
11	Kaberamaido	27	16	0	19
12	Katakwi	33	29	0	17
13	Kawete	2	0	0	2
14	Kumi	11	0	0	10
15	Lira	32	9	0	19
16	Molo	51	118	0	19
17	Mukuju	2	0	0	2
18	Munyole	1	0	0	1
19	Namutumba	54	153	0	19
20	Ngora	17	0	0	15
21	Oyam	5	0	0	5
22	Pasindi	30	3	0	19
23	Serere	8	0	0	8
24	Siwa	7	1	0	7
25	Soroti	55	134	0	19
26	Wawulera	13	0	0	13

Wawulera, Kumi, Bunyiza, Serere, Siwa, Adjumani, Mukuju, Buhonge, Buhangasi, Dokolo, and Amuru livestock markets had a relatively low movement of cattle in and out of the district.

The degree of betweenness and closeness and the k-cores are summarized in **Table 3**. Namutumba had the highest degree betweenness followed by Molo and Soroti, respectively. Namutumba was also observed to have the highest degree of closeness followed by Soroti and Molo. The correlation between closeness and betweenness was 0.8. Animal diseases such as rHAT are most likely to pass through Namutumba district, i.e., diseases are most likely to come into Namutumba district and easily passed to other districts *via* the cattle trade network.

Cattle markets with the highest k-cores were Kaberamaido, Lira, Molo, Namutumba, Pasindi, and Soroti. The analysis revealed several nesting cores. By limiting the number of k-cores, the members of the five-core, as a nesting core, were Soroti, Molo, Katakwi, Kaberamaido, Kumi, Lira, and Oyam. The five-core members may potentially be super spreaders of rHAT and are vulnerable to disease incursion. The key cattle market whose removal would disintegrate the network (articulation points) were Soroti, Namutumba, and Molo (**Figure 5**), representing key nodes where routine disease surveillance and control may be targeted to prevent spread of rHAT.

Examination of structural equivalence as shown in **Figure 6** revealed that there were four clusters, indicating similarities in the structure of cattle trade for each cluster. As shown in **Figure 6**, cluster one was comprised of Bukedea (ID 5), Bunyiza (ID 6), Munyole (ID 18), Dokolo (ID 9), Amolatar (ID 2), Siwa (ID 24), Busaba (ID 7), Adjumani (ID 1), Kawete (ID 13), Buhonge (ID 4), Mukuju (ID 17), Pasindi (22), Wawulera (ID 26), Amuru (ID 3), Serere (ID 23), Butangasi (ID 8), and Gulu (ID 10). Cluster two was comprised of Molo (ID 16) and Namutumba (ID 19). Cluster three was comprised of Soroti (ID 25). Cluster four was comprised of Kumi (ID 14), Lira (ID 15), Ngora (ID 20), Oyam (ID 21), Kaberamaido (ID 11), and Katakwi (ID 12). Network block modeling, a measure of similarity using nodes, revealed no single block that connected all others. Extraction of link clusters *via* single hierarchical clustering, as measure of similarity using links, showed five clusters in the network with a maximum partition density of 0.42, the largest having 11 nodes. Additionally, there were five link communities in the cattle network as shown in **Figure 7**.

From the community membership matrix, the most connected cattle markets (connected to five or more communities) were in the following order of connectedness: Molo > Soroti > Kaberamaido, Namutumba>Katakwi > Dokolo >Amuru >Amolatar > Pasindi (**Figure 8**). Livestock markets in SE Uganda comprised 66% of the top connected nodes in the cattle trade network. Limiting actor community membership for the top connected cattle markets to those belonging to three or more communities revealed Molo, Soroti, Kaberamaido, Namutumba, and Katakwi to be the most connected markets.

Sensitivity Analysis

Sensitivity analysis comparing unweighted and undirected and weighted and directed cattle trade network showed some differences in the k-cores and the top connected livestock markets. K-cores for each actor were twice than for those of a directed network. The top connected nodes in the undirected network were Namutumba, Soroti, Kaberamaido, Katakwi, Molo, Amuru, Lira, Pasindi, Kumi, and Ngora. Therefore, in the undirected cattle network, SE Uganda livestock comprised of 78%

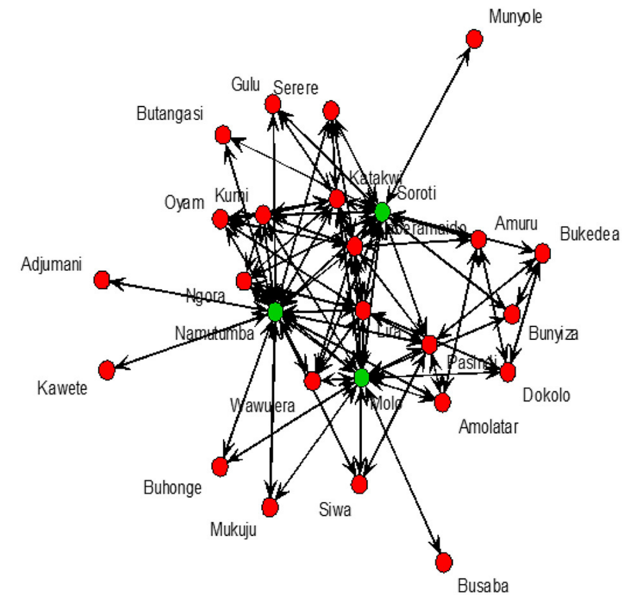

FIGURE 5 | Cattle markets where *T. b. rhodesiense* is likely to be spread from. Soroti, Namutumba, and Molo shown by green dots.

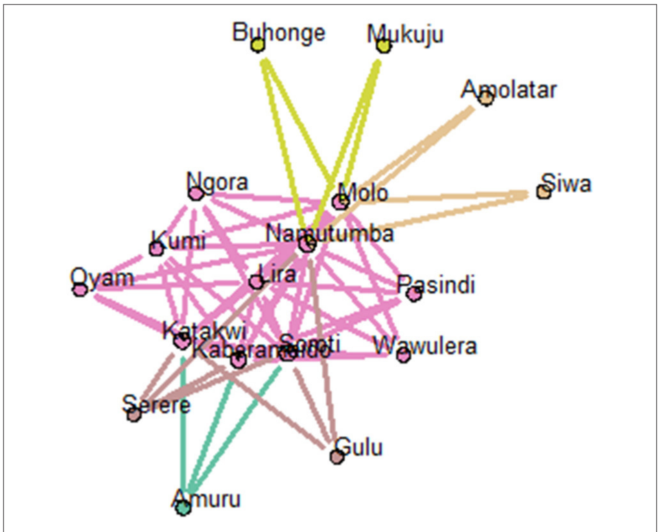

FIGURE 7 | Visualization of link communities within the cattle network (using node pies). The fraction of the total number of edges that a node has in each community is depicted using a pie chart.

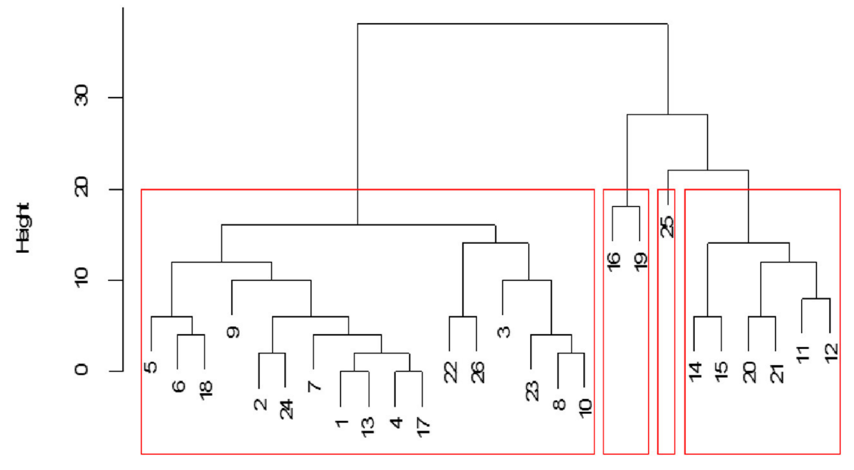

FIGURE 6 | Cattle market structural equivalence within the network. Numbers represent cattle market identification (ID), and red boxes indicate the cluster.

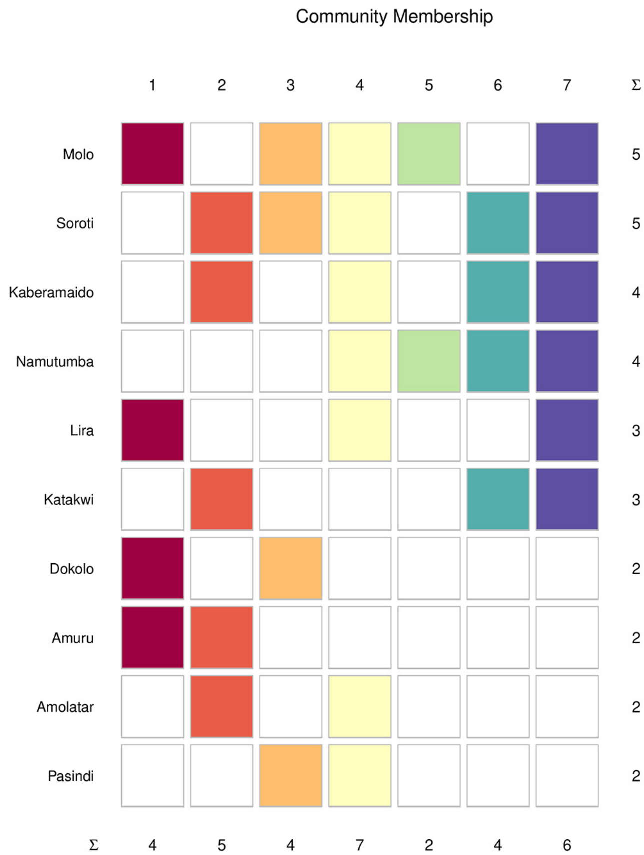

FIGURE 8 | Community membership of the top (most) connected cattle markets in southeast and northwest. Colors indicate the community-specific membership, and the N-Ary summation (∑) shows the total number of cattle markets in each community.

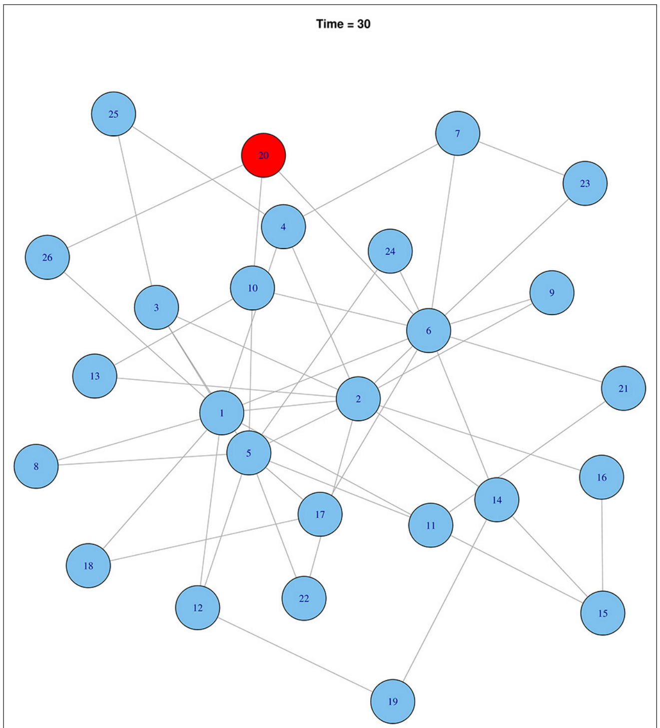

FIGURE 9 | Effect of controlling rHAT when using effective control methods after 30-time steps. Infected nodes are shown in red and uninfected in blue.

of the top connected nodes. The articulation points (cut points), which were Namutumba, Molo, and Soroti, were the same in both directed and undirected networks.

Simulated Disease Transmission

Starting from a random cattle market, it was simulated that rHAT would have spread to six cattle markets at the 30-time step. Using effective rHAT control methods such as combined cattle treatment and spraying would reduce the transmission to only one cattle market (**Figure 9**). In comparison to a highly infectious pathogen, 20 cattle markets would have been infected at the initial 30-time step (i.e., R_o 0.05) reducing to 12 cattle market when infectiousness was reduced by 50% (i.e., R_o 0.025), and eventually six cattle markets when infectiousness was reduced by a further 25% (R_o 0.0125) (**Figure 10**).

DISCUSSION

Trypanosoma brucei rhodesiense has rapidly spread through the cattle trade network in Uganda, moving infection progressively northward. Previous work confirmed the contribution of livestock movements through formal livestock markets and restocking in disease spread. Uganda is a source of meat for the East African community, Democratic Republic of the Congo, and Southern Sudan (11).

Human infective parasites were first observed in indigenous cattle in Tororo district in 1987 (52). *T. b. rhodesiense* HAT rapidly spread around the shores of Lake Kyoga causing significant human outbreaks that were associated with movement of infected animals (7, 9, 58) driven by a policy of restocking districts impoverished by war and generations of cattle raiding by the Karamajong. Restoration of peace in northwest Uganda and South Sudan is a significant driver for the trade and sale of livestock for meat between the two countries (11). Another potential driver of cattle is cattle prices. In this study, we found that cattle prices are influenced by biophysical characteristics and demand for animal traction, with adult male cattle and young male trained for plowing fetching the highest prices. Further analysis of factors underlying livestock movement is still required to be done.

Analysis of livestock movement data has been shown to be valuable mostly in high-income countries where such data are routinely collected. In developing countries, data on livestock movement detailing origin, destination, number of cattle sold, cattle prices, etc., are limited and in most cases unavailable. Equally, resources are not always available to routinely collect and collate such data for decision-making. By collecting cattle movement data from cattle traders, this study shows that it is

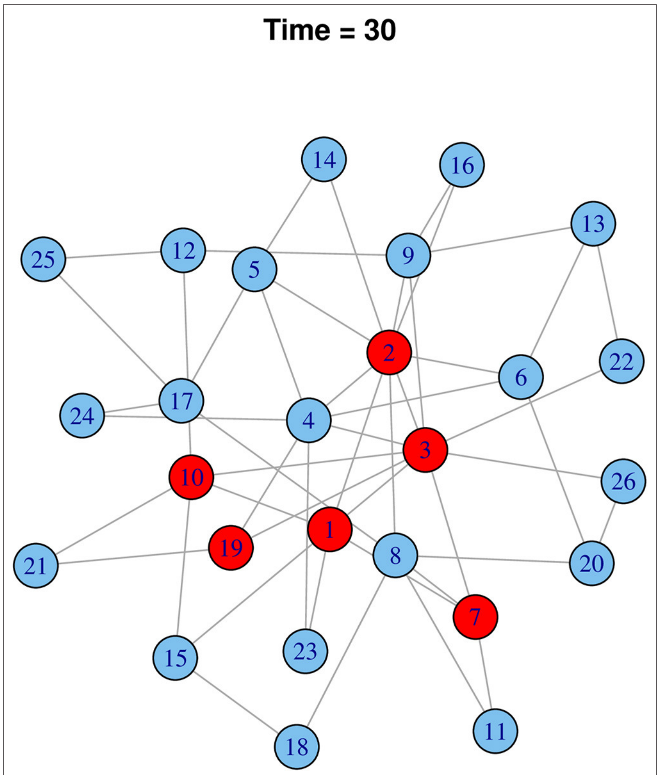

FIGURE 10 | Effect of controlling "fast" pathogen (R_o 3) when infectiousness is reduced to 25% (R_o 0.75) after 30-time steps. Infected nodes are shown in red and uninfected in blue.

possible to use expert domain knowledge to construct a network. The value of conducting livestock network analysis in resource-limited settings lies in the possibility of identifying key cattle markets that can be targeted for routine disease control, reducing costs and disease impact. Additionally, simulating animal disease spread enhances understanding of the effectiveness of disease control methods. For example, in this study, we show that for "slow" pathogens like rHAT, effective treatment strategies can sufficiently reduce the spread of rHAT. It has been shown that treatment of cattle using diminazene aceturate and spraying for tsetse flies to protect cattle against trypanosomiasis is effective and has high net benefits (86–88). Compared to "slow" pathogens such as rHAT, control of "fast" pathogens within the network may be problematic and costly requiring a wider coverage of cattle markets or a highly effective control method or methods. This is because even when disease infectiousness and transmission is reduced to 25%, the number of infected cattle markets was still substantial.

The cattle network examined here can be categorized as both connected and heterogeneous. Heterogeneity coupled with a low clustering coefficient, asymmetry. and high skewness as found in this study is typical of scale-free networks (89). The low density (0.3%) and clustering coefficient (0.5) indicate that the cattle trade network has a random pattern, making it difficult to predict a future likely source of rHAT. Cattle and poultry trade network studies in Madagascar (4, 41) showed a similar weakly connected network with low density and clustering coefficient. The average centrality value for the cattle trade network in this study was low, indicating that cattle are being moved through few connections, most likely as a result of majority livestock traders in Uganda operating at small scale. While low connection within the trade network raises the probability of low disease detection, it does offer opportunity to control disease spread within the network.

Examination of degree centrality and betweenness revealed that Soroti had a high cattle movement in and out the district, whereas most cattle passed through Namutumba. Therefore, rHAT and other infectious diseases can easily start at this district or be passed to other districts. Equally, most animal diseases can easily be transferred to Namutumba district and passed to other districts. In the past, Soroti was an epicenter of rHAT outbreak in 1999/2000 which was linked to Brooks Corner livestock market (currently in Serere district) (7).

The study also identified a core group (five-core) of cattle markets that are vulnerable to rHAT and perhaps other animal diseases and may act as superspreaders. The members of the core group were the most connected markets, with the highest flow (in and out) of cattle, and they were found in the eastern and northwest districts of Uganda, increasing the probability of spread of rHAT from the endemic southeast parts to the non-endemic northern parts of Uganda. Members of the core group in eastern Uganda included Namutumba, Molo, Soroti, Pasindi, Wawulera, Ngora, Kumi, and Katakwi whereas northern Uganda markets included Oyam and Lira. This core group would maintain infection and serve as an epicenter for the spread of infection to other cattle markets in Uganda, particularly if the original infection was from Namutumba, Soroti, or Molo livestock markets.

Cattle markets that connect southeast and northwest Uganda play a key role in the spread of pathogens. Consequently, Government policy dictates that cattle sold at markets should be treated with trypanocidal drugs prior to sale to prevent movement of *T. b. rhodesiense*-infected cattle. Implementation of this policy, however, is not straightforward. It is the responsibility of the purchaser to pay for both the trypanocides (∼US$0.30 per animal for treatment with curative diminazene aceturate to US$0.75 each animal for treatment with isometamidium chloride which has a 3-months prophylactic effect) along with the veterinary fees for administering the treatment (∼US$0.30 per animal). Most cattle markets are not perimeter secure, resulting in buyers frequently avoiding extra costs by leaving. Another challenge is that animals purchased for subsequent slaughter should not be treated with trypanocides or should only be slaughtered after the withdrawal period of such trypanocides. Aside from the requirement to treat cattle in livestock markets, Uganda law also decrees that any animal destined to move across district boundaries has the correct permit for passage between the specified districts. Ideally, permits should be issued by qualified veterinary personnel subject to animals passing an inspection (examination of clinical manifestations of any communicable disease). Permit records should be kept by the District Veterinary Officer's office from the market of issue, with duplicates dispatched to the Ministry of Agriculture Animal

Industry and Fisheries, Entebbe. However, implementation of all the required laws is challenging. Therefore, from a practical point view, network analysis can be used to inform risk-based and targeted disease surveillance and control to circumvent some of the challenges in implementing disease control laws.

This study had limitations. First, livestock markets and cattle traders in northern and some parts of eastern Uganda were not interviewed, as the study was focused on rHAT and lacked resources to expand to other parts of the country. This resulted in a relatively smaller sample size which may affect the cattle network metrics. Second, the study relied on past *T. b. rhodesiense* prevalence as an attribute given that no blood samples were taken from cattle. Consequently, further research on livestock markets as well as sampling for *T. b. rhodesiense* is recommended. Third, the cattle network does not incorporate dynamic patterns such as seasonality, thereby limiting its complexity; longitudinal collection of cattle movement within a set period, e.g., 1 year, is required. Further limitations include use of a simple epidemiological model to simulate disease control; sophisticated modeling may make substantial differences in disease transmission more apparent.

This study recommends (i) control through chemotherapy and spraying of cattle with tsetse-effective insecticides and targeted surveillance of rHAT in key cattle markets (nodes) such as Namutumba, Soroti, and Molo cattle markets as opposed to untargeted disease control that may be costly, (ii) further targeted and routine surveillance in cattle markets in eastern and northwest Uganda to detect the presence of rHAT in cattle, and (iii) additional collection and analysis of livestock movement data from more cattle markets to understand animal disease risk. Spraying of cattle with deltamethrin using the restricted application protocol in addition to cattle treatment with curative trypanocides at the point of sale (e.g., in the cattle markets) is recommended by (7, 51). Trypanocidal drugs capable of temporarily clearing cattle of the human infective parasite are well-understood and widely available; tsetse-fly-targeted insecticides to prevent reinfection of cattle are also well-understood and widely available (89–97). The restricted application approach (RAP) to insecticide use at markets will reduce costs and is practically feasible (98). However, farmers require support for management of disease and policy to treat animals for the prevention of spread of diseases such as trypanosomiasis and tick-borne diseases needs to be reinforced (99, 100). Furthermore, indigenous cattle are predominantly kept under traditional communal grazing management and are either tethered or grazed on communal pastures. Under these management systems, cattle are exposed to continuous tsetse and tick challenge and the new strains of tsetse and tick-borne diseases (trypanosomiasis, anaplasmosis, babesiosis, and theileriosis) imported are difficult to contain following their introduction.

CONCLUSION

Trypanosoma brucei rhodesiense can potentially be spread both within southeast and between this region and northwest Uganda by cattle trading. Targeted *T. b. rhodesiense* surveillance in cattle markets in southeast and northwest Uganda would enable early disease detection. Reinforcement of government policy for treatment of cattle at the point of sale through trypanocidal treatment and spraying to protect them from reinfection should be prioritized in eastern Uganda to limit spread of infection. The combined impact of these two interventions (i.e., trypanocidal injection and insecticide spraying), through public–private partnerships, will reduce the risk of reinfection caused by cattle moving into rHAT previously affected as well as unaffected regions of Uganda.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Makerere University College of Veterinary Medicine Animal Resources and Biosecurity ethical review board, and by the Uganda National Council for Science and Technology (approval number HS1336). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

WO was responsible for the conception, design, collection, drafting, and analysis of data. DM and CA were involved in the conception of the study and data collection. AS was involved in the conception, design, analysis, and drafting the manuscript. SW and CW were involved in the conception of the study, design, and revision of the manuscript. EM was involved in the design and drafting of the manuscript. All the authors read and approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.611132/full#supplementary-material

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Digital Extension Interactive Voice Response (IVR) mLearning: Lessons Learnt From Uganda Pig Value Chain

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We assessed the effectiveness of Interactive Voice Response (IVR) technology in delivering biosecurity messages for the control of African swine fever (ASF) in Uganda using a randomized controlled trial (RCT) with 408 smallholder pig farmers. Our results show that IVR technology significantly improved knowledge of farmers who had not been exposed to training on biosecurity. Furthermore, it enhanced knowledge for farmers who had received face-to-face (f2f) training in biosecurity. This group of farmers recorded the highest knowledge gain following IVR training compared to farmers who did not receive f2f training. IVR technology was perceived by farmers as a new technology capable of transforming their lives because it is time efficient, has high potential for resource saving and flexibility. IVR also seems to be gender sensitive as it addresses some of the constraints women face in accessing conventional extension services such as time. IVR is an innovative way for delivery of advisory information to pig farmers. The scalability of IVR technology could further be explored and its feasibility assessed for wider use by the extension systems in Uganda and elsewhere.

Keywords: interactive voice response, participatory training, biosecurity, pig, Uganda (Sub-Saharan Africa)

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BACKGROUND

Agricultural extension/advisory services in Uganda face many challenges due to lack of capacity of the government to support long-term interventions. This stems from the fact that the public services since structural adjustment in the 1980s have pulled out almost entirely from their leading role as extension service provider. Thus, most farmers in many areas are left fending for themselves. Development organizations have attempted to fill in the gaps but with very limited success, considering the temporary nature of their programs. Research has shown that farmers' exposure to information is a key driver influencing their adoption of technologies and best practices (1). Individual and group face-to-face (f2f) extension methods have been the standard ways to channel information to farmers. However, these approaches have their limitations such as high cost of delivery (2), insufficient funds for supporting public extension, limited involvement of rural farmers and populations, particularly women in extension processes, and lack of research and appropriate extension methods (3). This limits coverage of extension services, particularly across rural regions, and adapting technological packages to community-specific contexts (4). Given the situation, farmers require enough information and exposure to the latest approaches to make use of science and technology in the field of agriculture to increase productivity of livestock and crops. Over the last decade, largely due to the spread of mobile phone technology in rural areas, Information and Communication Technology (ICT) demonstrated the positive and significant impact they can have on economic development by improving the business environment in rural areas (1). In the present times of technological development, mobile technology particularly mobile phones has become the most important tool of communication which can be accessed by farmers for agriculture-related information and knowledge (5). In Uganda, access to mobile phones had increased from 0.13 to 25 million people between 2000 and 2018 (6). The increasing access and use of ICT tools by smallholder farmers provide an opportunity to improve communication, thus relaying critical information and knowledge to farmers in situations where resources, both financial and human, are limited. These ICT tools when properly applied in the context of the overall extension and advisory services system have the potential to address in a timely and effective manner the existing challenges being faced in the area of extension and advisory services by many livestock farmers in developing countries such as Uganda. These technologies hold the potential for reaching significant scale at a relatively low cost, so there is an interest to better understand this "scaling mechanism" so that it can benefit extension systems working on similar issues in the nexus of research to development.

It is against this backdrop that we have partnered with local district government to pilot test innovative ways through ICT to deliver information to smallholder pig farmers in Uganda. Our objective is not to replace conventional f2f extension methods, but to augment extension and advisory service programming through the integration of appropriate ICT tools. We chose Interactive Voice Response (IVR), as a potential ICT tool to deliver critical information to pig farmers in Uganda. IVR is a telephony system that interacts with callers, records information, and directs calls to an appropriate database of prerecorded information in voice form. An IVR system can accept telephone input through the touch-tone keypad selection and provide the appropriate response in the form of voice. This technology has been used in the area of human healthcare to provide opportunities to educate as well as to monitor individuals on their self-management behaviors (7). It has also been used in agricultural extension in India (8) and Tanzania (9) to improve its efficiency of prevalent services. The area of application of biosecurity for the control of African swine fever (ASF) in smallholder pig systems was identified as an interesting pilot case for Uganda. This is because timely provision of biosecurity information and knowledge to pig farmers is considered the most effective way for controlling ASF since there is no vaccine available in Sub-Saharan Africa so far. However, adoption of biosecurity measures is highly dependent on a farmer's knowledge about the best practices and their incentive to apply them adequately (10, 11).

Another reason why we chose biosecurity is the ongoing work since 2015, originally part of the CGIAR Research Program on Livestock & Fish, now part of the CGIAR Research Program on Livestock (hereafter Livestock CRP) in Uganda, which included a Randomized Controlled Trial (RCT) across several sites that looked at the effects of traditional extension activities such as participatory training (referred here as f2f training) on Knowledge Attitude and Practices (KAP) of pig farmers on biosecurity. Results showed that there was a significant effect of biosecurity training on gain in knowledge by pigs farmers in target sites (11). The RCT had a baseline, as well as two consecutive monitoring assessments of treatment and control groups with regard to the biosecurity aspects of ASF. By leveraging this ongoing work, we expected to come up with interesting insights on whether and how the addition of digital extension (IVR technology) can augment conventional f2f training. Specifically, the work built on existing research partnerships in Uganda and supplemented these with technical expertise, knowledge, and skills in converting learning materials and modules into digital format, notably IVR, so that semi-literate and semi-numerate livestock owners can improve their knowledge about pig husbandry and animal healthcare. The study addressed the following research question: does IVR technology enhance traditional training approach? Therefore, the objective of the study was to evaluate the effectiveness of IVR technology on farmer knowledge about biosecurity. The study also documented perceptions of pig farmers about digital extension and provided learning and experiences on the role of ICT in strengthening extension systems and their scalability potential in the context of smallholder pig systems in Sub-Saharan Africa.

MATERIALS AND METHODS

Study Area

The study was carried out in Masaka district where an RCT to evaluate the participatory f2f training was being implemented. Masaka district is located in the central region and has the highest pig population density in Uganda (>50 heads/km²) (12). Pig farming is an important economic venture for smallholder farmers who often keep a small number of pigs for income generation. Masaka district was part of the "Smallholder Pig Value Chain Development Project" (SPVCD) in Uganda, which is a research for development program running since 2011 to improve pig value chains in the country (13). In each district, villages with high pig population density were identified from census data. Areas with the highest ASF outbreaks, based on records from respective district veterinary offices, were considered as a proxy for high ASF prevalence. Villages were randomly and equally allocated to treatment and control groups.

Randomization

The design of the study allows for evaluation of the effects of f2f participatory training (P), the effects of IVR messaging (V), and the interaction of participatory training and IVR messaging, or the combined effect of training with IVR messaging. It followed a complete factorial design with participatory training (yes/no)

TABLE 1 | RCT arms and actual numbers of farms/households who have participated in the study.

Village	Group 1	Group 2	Group 3	Group 4	Total
	No participatory training and no IVR messaging (P–V–)	**Participatory training and no IVR messaging (P+V–)**	**No participatory training and IVR messaging (P–V+)**	**Participatory training and IVR messaging (P+V+)**	
Kanyaga	30	–	–	–	30
Luwerekera	26	–	–	–	26
Butego	26	–	–	–	26
Kirumba A	24	–	–	–	24
Lukindu	–	28	–	–	28
Butaano	–	24	–	–	24
Kalagala	–	21	–	–	21
Kiyimbwme	–	27	–	–	27
Minyinya proper	–	–	29	–	29
Zzimwe	–	–	29	–	29
Mwalo	–	–	19	–	19
Kamugombwa	–	–	25	–	25
Sserinya	–	–	–	27	27
Nkoma	–	–	–	24	24
Kikumba–Katwe	–	–	–	25	25
Kyabakuza	–	–	–	24	24
Total					408

and IVR messaging (yes/no) as the two factors. This provides four groups of individuals (**Table 1**; **Supplementary Material 1**):

The selection of subcounties carried out during the previous RCT and this study utilized the same subcounties. Villages for groups 2 (P+V–) and 4 (P+V+) also came from the previous study with selection of new villages for groups 1 (P–V–) and 3 (P–V+) following the same criteria as described above (11). Because of the need to utilize villages from previous study, the randomization of villages to group was only carried out for the IVR factor. This means that villages from the previous study were randomized to be V– or V+ (groups 2 and 4) and the new villages were also randomized to be V– or V+ (groups 1 and 3).

Sample Size Calculation

Sample size calculations for the main effect of participatory training and IVR messaging used a two-sample binomial proportion comparison between the two pairs of groups (i.e., P+ vs. P– or V+ vs. V–) for the response indicator of farmer knowledge. Similar to the previous RCT, the calculation assumes a 30% difference in knowledge (35 vs. 65%) between these as being significant. For the interaction effect, the same calculation was used but for comparisons made between any two groups. Allocation of individuals to group was carried out at the village level to ensure no spillover between individuals across the different groups. Therefore, sample size calculations were adjusted for intra-cluster (village) correlation (ICC), assumed to be low for the IVR messaging as this technology is aimed directly at individuals, but for participatory training, we use the ICC obtained during the previous RCT (0.38). The sample size utilized here is the most conservative required, i.e., 30 households per village derived from the power calculation. However, some villages had sample sizes slightly <30 because some farmers withdrew from the study or did not show up during training. However, this situation did not affect the quality of the study (**Supplementary Material 1**).

Description of Extension Technologies

Participatory Training

The process of participatory training was described elsewhere (11). Prior to the study, a training manual was developed by the project team (14). The content of the training was focused on transmission and spread of ASF as well as measures for its control and prevention. Emphasis was put on key biosecurity measures that could make a difference in the control of ASF such as pig confinement, farm visit restriction, management of sick animals, disposal of dead animals, processing of swill, disinfection, and outbreak reporting. The manual's content and the training approach were, respectively validated and tested with farmers and district veterinary extension personnel. The training of farmers was administered by extension staff from respective district veterinary offices to all consenting pig farmers in the villages that belonged to the treatment group. The extension officers were trained by the project team on how to administer the training. Farmers were split into groups of 20–30 people per training session which lasted ∼4 h. The training course was made of five sessions: ASF causes, symptoms, and transmission (1 h); biosecurity measures at farm level (1 h); proper control of pig movements and reporting (30 min); on-farm practical demonstration of biosecurity measures (1 h); and training evaluation (30 min). Since the target of the training was to improve farmers' knowledge of biosecurity, we focused on knowledge and skill-based lessons.

Several delivery methods were used during the training including plenary brainstorming, small-group discussion, story storytelling and practical demonstration of cleaning and disinfecting a pigsty, construction of a footbath, hand washing and disinfection, use of protective wears, swill processing, and disposal of dead pigs. Various tools/aids were used to relay the messages including photos (of diseased pigs), posters, film clips, and drawings. Farmers who faced ASF outbreaks could share their experiences with others to stimulate discussions among participants who then reflected on the strength and weaknesses of the biosecurity measures they applied to control the disease.

Development and Implementation of the IVR mLearning

Content

We designed the training course on biosecurity measures for ASF disease based on training manuals used during the f2f participatory training sessions. To adapt this content into IVR audio files, we followed a two-step process. Firstly, the f2f training manuals were curated to create brief lesson paragraphs ensuring that each paragraph contained one or two key information points that we intended the farmer to take up; this was done to avoid overload to the farmer and limit the lesson to information that the farmer could immediately try on their farm. Secondly, using a performing arts team, we adapted this technical and "classroom" type of content into a drama series set in the local context and recorded in one of the highly used local languages, Luganda. The drama series approach was used to make the content interesting and relatable to the farmer with an objective of making it easier to be remembered and enhance the chances of finishing the 10-part lesson.

System Design of the IVR mLearning Training Prototype

Our IVR system was an in-house prototype consisting of hardware, software, and telecommunication infrastructure service to provide the connection. The system ran on a Centos operating system upon which we installed the telephony application *Asterisk IVR PBX* by Digium and developed a python script to run the commands. The system was installed in a standard personal computer (PC) with a peripheral component interconnect express (PCIe) slot to accommodate the digital telephone interface card (Digium TE122P PCI Card) for the E1 Connection that was used for the voice service. The fiber connection was provided by a local Telco MTN *via* fiber connection. This system has the capacity of handling up to 900 simultaneous calls, which was considerably higher than our target group of 240 participants. The staff support required for creating and maintaining the system included (1) a content specialist/epidemiologist to provide the content needed by farmers; (2) an ICT4D business analyst who understood the problem by the epidemiology team and designed the ICT solution that would best solve the problem; (3) an ICT technician to install the software and maintain the service; and finally (4) a performing artist to adapt the content into a voice-recorded drama series.

Training via IVR mLearning System

To raise awareness on the digital training course, we mobilized participants through the local government offices and extension workers, and the decision to participate was voluntary and formalized with a signed agreement. Participating farmers were then registered *via* their mobile phones and asked to indicate the time and day of the week they preferred to receive the IVR call. The course was designed to play two sessions a week unless the farmer opted to increase the occurrence of the sessions to a maximum of four a week to avoid information overload and possibly affect retention and adoption. The IVR system would then make the calls at the scheduled times. If a farmer needed to receive the call at any other time different to the registered time, they would call the system and the system would terminate the call and immediately return the call. The technology was only available to the registered farmers. Once the system called the farmer and the call was received, an introduction to the course and process was done followed by a lesson and a quiz. Depending on whether the farmer answered correctly or not, the system would determine whether they proceeded to the next lesson or would repeat the lesson once. The farmer would proceed this way until they completed the final lesson number 10 where they would be informed of the end of the course and thanked for their participation. After each call, the farmer had options to also repeat the lesson voluntarily, play the next lesson, or leave a message to the training team. A sample IVR flow is presented in **Figure 1**. The project assumed all costs and included free airtime as an incentive for answering post-lesson questions correctly, which was also a prerequisite for moving on to the next lesson (**Figure 1**).

Evaluation of the Interventions

The f2f participatory training began in April 2015 and lasted for 1 year (until May 2016), while the IVR technology which lasted 6 months started with a pilot on May 16, 2018, and ended on November 19, 2018, followed by an assessment (using the same/similar assessment template/indicators as the original project, for comparability). A few questions were added to the standard assessment tool to capture perceptions of farmers toward the technology and document lessons learnt. Prior to applying the technology, a baseline survey similar to the one carried out during the previous project was conducted to assess the level of knowledge of farmers about biosecurity and ASF control in all four RCT arms. Three months after administration of the IVR technology, the same survey was repeated to evaluate changes (knowledge gain by farmers) made by the training. In addition, 120 of the farmers who received the IVR training responded to the question that aimed at assessing their perception about the technology and document challenges they faced during the training.

Data Collection and Analysis

Field data collection and processing was carried using CSPro whereby initial data cleaning and validation was done. The cleaned data was then exported to STATA 16 for advanced data processing and analysis. The five-Likert scale system used during field data capture was recoded into a binary format

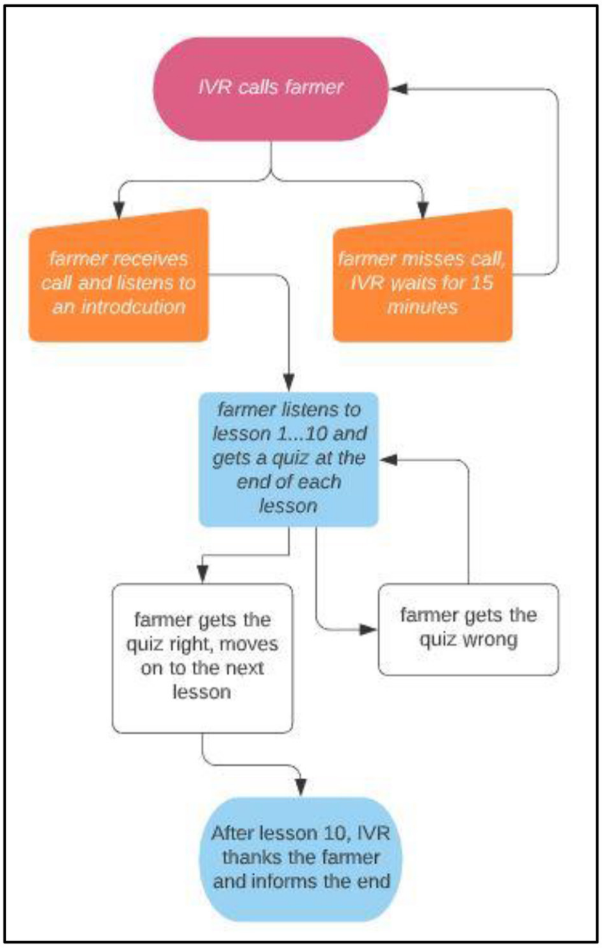

FIGURE 1 | IVR processing diagram.

(1, 0) whereby a value of 1 represented a scientifically correct response while 0 represented the wrong or undesired response. The recoding was necessary to adjust to the unidimensional scale, which is a fundamental assumption of the Item Response Theory (IRT) model, procedures for analyzing and obtaining information about the respondents, the questions asked (items), and the latent variable measuring the level of biosecurity practices among interviewed farmers. Using IRT, items that correctly captured the latent variable based on the discriminatory powers were retained in the model while those that did not were excluded. The retained items (questions) were used to fit a two-parameter logistic (2PL) IRT model to generate item characteristics curves (ICC), and item information functions. In the 2PL, the respondent's choice of the correct or wrong answer is dependent on the respondent's ability (knowledge) level, the item difficulty, and its discrimination. Item discrimination is the degree to which an item differentiates individuals with high knowledge level from individuals with low knowledge level, while an item's difficulty reflects the knowledge or level required for a respondent to have a 50% chance of answering the question (item) correctly. The individual respondent's overall knowledge (latent trait—designated theta) was estimated using an empirical Bayes estimator. Change in knowledge calculated as the difference between "after" training and "before" theta scores was then analyzed using a mixed-effects linear model with village as the random effect.

RESULTS

Demographic Characteristics of the Participants

A total of 408 households participated in the pre- and post-training surveys, in four different groups. Group 1 (P–V–) had 99 participants, group 2 (P+V–) had 100 participants, group 3 (P–V+) had 102 participants, and group 4 (P+V+) had 107 participants. Although most of the sampled households (76%) were male headed, 58% of the respondents were female (**Table 2**).

The average age for respondents in both the treatment and control groups was 47 years with standard deviation of 14. Crop, pig farming, self-employed off farm, and salaried were the main sources of income for households in all groups (**Figure 2**). Overall, 14% of the respondents belonged to farmer groups with more respondents from the P+V+ group (27%) belonging to farmer groups, followed by P–V+ group (13%). P+V– and P–V– were all at 8%.

Impacts of Training on Farmers' Knowledge

The percentage of P+V+ respondents correctly answering biosecurity questions consistently increased between phase 1 and phase 2 compared with other groups particularly P–V– group, which showed inconsistency (**Appendix 1**). Each biosecurity question was assessed for consistency using the IRT method, and their discriminatory and difficulty coefficients were generated (**Appendix 2**). The question on whether housed pigs "catch" ASF or not was the most difficult question with a coefficient of 1.13 and overall percentage of households correctly responding to it being less than 50% in both phases. This question was also the least discriminating question (discrimination coefficient = 0.31). The most discriminating question was the one of whether disinfecting farm tools controlled the spread of the disease or not which had a coefficient of 2.21. **Figure 3** is the graphical representation of item difficulty and discrimination coefficients for each biosecurity question.

Individual knowledge gain was calculated as the change in an individual household's knowledge scores between phase 1 and phase 2 (**Table 3**). A positive knowledge gain showed an increase in knowledge after intervention (training) while a negative knowledge gain showed a drop in knowledge. Use of participatory methods showed a higher knowledge gain than other methods; use of IVR showed a smaller knowledge gain compared to non-IVR for both the trained and non-trained groups.

Figure 4 shows the least-square mean knowledge changes; the group who received both participatory training and IVR (P+V+) recorded a significantly higher change in knowledge scores than groups that did not receive participatory training (P–V+ $p = 0.030$, P–V– $p = 0.003$). There was also evidence that

TABLE 2 | Household demographic characteristics (%).

Characteristics	Variable	P+V+ (*n* = 107)	P+V– (*n* = 100)	P–V+ (*n* = 102)	P–V– (*n* = 99)
Sex of household	Male	66	72	67	66
	Female	34	28	33	34
Sex of respondent	Male	28	45	24	34
	Female	72	55	76	66
Highest education level	No education	3	6	2	2
	Primary	49	50	60	69
	Secondary	35	29	33	26
	Post-secondary	12	15	5	3
Respondent role in the farm	Daily management	98	99	99	96
	Marketing	2	1	1	4
Number of respondents	99	100	102	107	

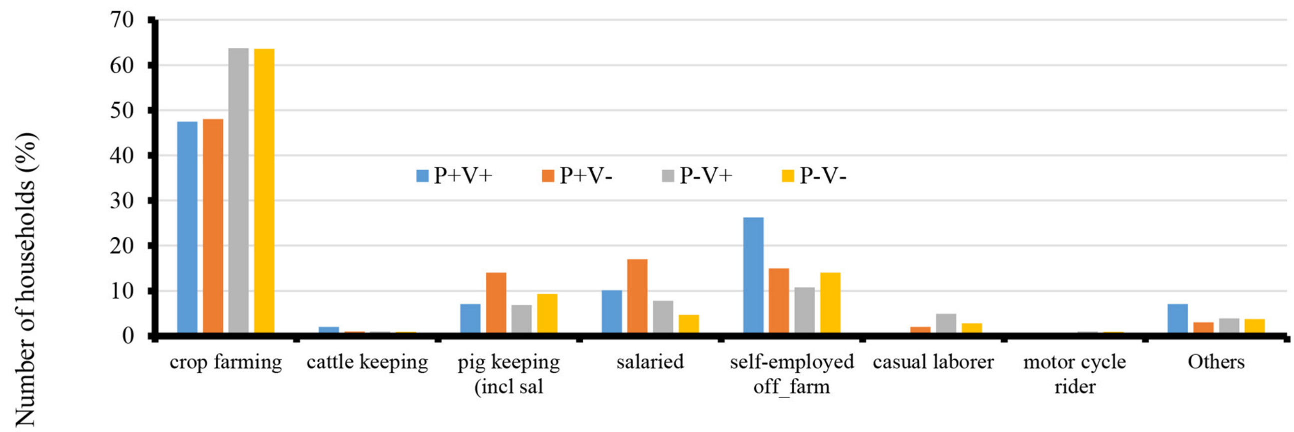

FIGURE 2 | Main household income sources for the farmers.

participatory training alone (P+V–) showed significantly higher gain in knowledge scores than no participatory training (P–V–) ($p = 0.014$). However, there was no significant difference in knowledge scores between the group receiving both participatory training and IVR (P+V+) and the group that received participatory training alone (P+V–) ($p = 0.635$) or between farmers receiving nothing (P–V–) and those receiving IVR only (P–V+) ($p = 0.462$).

A linear mixed model was used to test for differences between groups after adjusting for household characteristics and village as the random effect. Results from the linear mixed model are presented in **Table 4**. The only significant variables in the model are the group variable and farmer's years of experience. Farmers who had several years in farming experience showed a smaller increase in knowledge as compared to newer farmers ($p = 0.012$).

Perception of Farmers About IVR Technology

IVR Access and Use

One hundred and twenty farmers participated in the evaluation of the IVR access. Ninety-one percent (91%) of farmers rated their experience with the IVR as good to very good. Half of the farmers had received at least three training sessions with 39% receiving 6–10 training during the pilot phase. Most farmers (88%) had used their own mobile phone, while the remaining used those of their spouse, child, or neighbor. Seventy-three percent of farmers think that the audio-recordings of the training sessions were of good quality, and almost all farmers said they would welcome back the training (**Table 5**).

The Process

Figures 5, **6** present the responses of the farmers to the evaluation question of the IVR technology. The majority of farmers believe that IVR is fit for purpose, meaning the course was mapped to their real needs since the content was adequate; hence, they were able to improve their knowledge about pig management and control of ASF. They also mentioned that training was efficient and effective in the sense that it was flexible in time since farmers could schedule their own session at their desired time of the day (especially after routine home work). Some quotes from farmers supported these statements:

"It (the IVR) doesn't consume time like when farmers go for face-to-face trainings and at times the teachers don't appear yet with the mobile phone technology even if one is doing his or her work

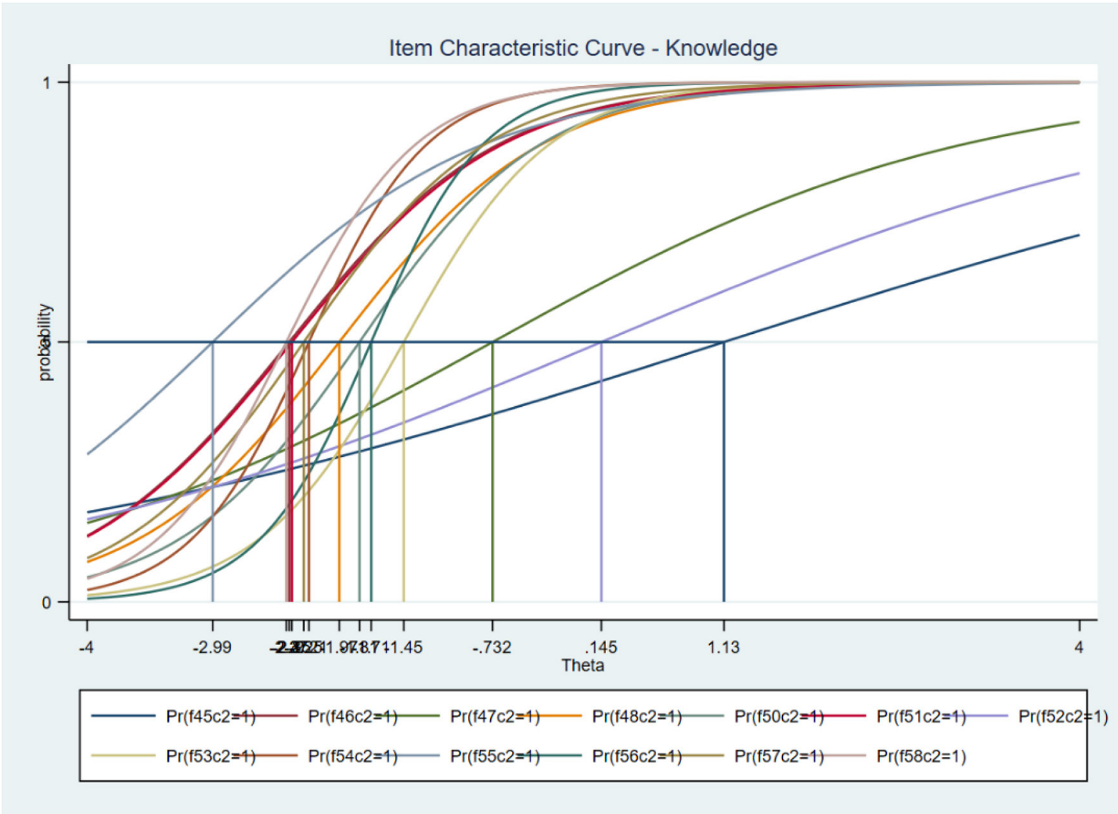

FIGURE 3 | Item characteristic curve.

TABLE 3 | Average knowledge gain by group.

Group	Mean knowledge gain	Std. dev.	N
P+V+	0.82	0.89	99
P+V–	0.77	0.96	100
P–V+	0.44	0.88	102
P–V–	0.30	0.84	107
Total	0.58	0.92	408

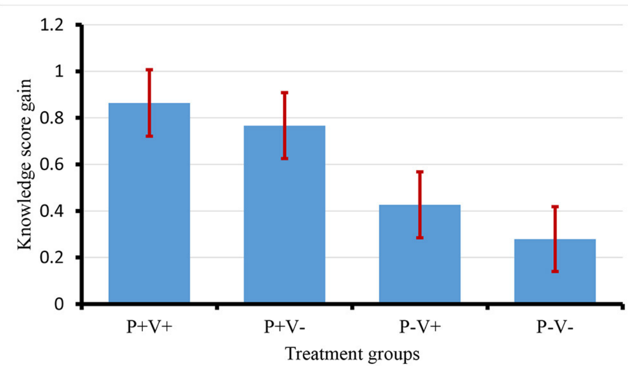

FIGURE 4 | Adjusted knowledge change scores by group (standard error bars shown).

can just pause a bit to learn and resume to work" (women farmer from Masaka)

For some farmers, it was important that farmers could log in and out to the training regardless of their physical position. This is illustrated with the following quote:

"It is a lifelong learning anywhere you can learn" (women farmer)

Most importantly, the IVR training was resource sensitive since farmers said they could save money through transport fees which they would have spent for f2f training. The training also enabled farmers to navigate across several sessions and hence decide which topic they are more interested to learn. The interactivity of the IVR was perceived as useful since automatic reminders could be sent to farmers about the topics to be covered in subsequent training sessions. The quote below denotes the importance of the feedback loop.

"Trained in time and always reminded on previous topic before moving to next topic" (male farmer)

TABLE 4 | Parameter estimates and significant of variables influencing knowledge gain.

	Wald $chi^2(11) = 23.64$, log restricted-likelihood = −507.58, Prob > $chi^2 = 0.0143$					
Knowledge gain	**Coef.**	**Std. err.**	**Z**	***P*** **> z**	**(95% conf. interval)**	
Group (P+V+)	0	–	–	–	–	–
P+V–	−0.096	0.203	−0.48	0.635	−0.494	0.301
P–V+	−0.438	0.202	−2.17	**0.030**	−0.833	−0.042
P–V–	−0.584	0.199	−2.94	**0.003**	−0.974	−0.194
Gender of farmer (male)	0	–	–	–	–	–
Female	0.147	0.139	0.11	0.916	−0.258	0.288
Education level (no education)	0	–	–	–	–	–
At least primary education	−0.021	0.094	−0.22	0.827	−0.204	0.163
Experience in pig keeping (in years)	−0.013	0.005	−2.53	**0.012**	−0.023	0.003
Belong to group (months)	0	–	–	–	–	–
Yes—belong to group	−0.087	0.136	−0.63	0.526	−0.354	0.181
Marital status (married monogamous)	0	–	–	–	–	–
Married polygamous	−0.175	0.196	−0.89	0.371	−0.560	0.209
Widow/widower	0.244	0.178	1.37	0.170	−0.104	0.592
Divorced/separated	0.169	0.210	0.80	0.421	−0.242	0.580
Single	−0.235	0.164	−1.44	0.151	−0.556	0.086
_cons	1.057	0.175	6.04	0.000	0.714	1.400

Among the drawbacks reported by the farmers (∼30%), the follow-up calls were mainly mentioned to be happening during an inappropriate time of the day, especially when farmers are busy (**Figure 7**). Women complained more about this situation. Another point women complained about was the poor quality of the recording. The quotes below denote challenges reported by farmers. Some technical challenges occurred for some farmers mainly related to quality of the phone device and the availability of the network, both leading to poor quality of the tone.

"The phone could go off, the language used was not clear and I could not understand and lastly i love to learn through the participatory way of teaching" (woman farmer)

The f2f training was still seen as very important since trainers could interact longer with training participants and field demonstration could also be done easily. The quotes below show the limitation of the IVR training according to farmers.

"The farmer understands better during face to face trainings" (woman farmer)
"The mobile phone training is not so friendly to me since I forget to connect" (woman farmer)
"It doesn't give time for one to think through what one can ask for thus a farmer failing to answer one's expectations" (woman farmer)

Technical Challenges Faced During Implementation of the IVR Technology

During the implementation of the IVR training, the researchers documented some technical challenges that could have contributed to the poor quality of the services highlighted by some farmers.

- Some farmers were not comfortable with the interactive nature of the IVR and often pressed the wrong phone device keys which lead to frustrations. Future deployments should minimize interactiveness as much as possible.
- Unreliable power source led to system downtimes that were impossible to pre-warn the farmers on. This can affect the perception of reliability of digital extension to farmers and affect future deployments. While future deployments might consider backup power generators, the associated higher costs would be better invested in going for a commercial system instead that would guarantee against this power problem.
- An in-house system in place of a commercial one suffered from recurrent lack of round-the-clock support to ensure the system stayed live; downtimes over the weekend and early evening were most affected as they would only be resolved at the earliest formal working day and hours. Adopting a commercial system would take care of this problem.
- The listening experience is also dependent on the quality of the mobile phone, and for some farmers, the phone was not audible enough.

DISCUSSION

In the context of agricultural development, information and communication technologies have played an important role in developing countries. ICTs are proving new approaches for communicating and sharing the information among livestock farmers (15, 16) to improve their knowledge and skills. Among modern ICTs, mobile phones serve as a means for effective transfer of knowledge and information about agricultural market

TABLE 5 | Responses of farmers to the evaluation survey.

Category	Men	%	Women	%	Total	%
What is your overall experience of using mobile phones to complete on-the-farm training						
Very good	14	42.4	30	34.5	44	36.7
Good	17	51.5	49	56.3	66	55.0
Bad	2	6.1	7	8.0	9	7.5
Very bad	0	0	1	1.1	1	0.8
Total	33	100	87	100	120	100.0
How many refresher trainings have you had since the start of the pilot?						
None	8	24.2	14	16.1	22	18.3
1–2 trainings	7	21.2	30	34.5	37	30.8
3–5 trainings	1	3.0	13	14.9	14	11.7
6–10 trainings	17	51.5	30	34.5	47	39.2
Total	33	100	87	100	120	100.0
Whose mobile phone are you using for this service						
Mine	32	97.0	74	85.1	106	88.3
Son/daughter	0	0.0	3	3.4	3	2.5
Spouse	1	3.0	9	10.3	10	8.3
Neighbor	0	0.0	1	1.1	1	0.8
Total	33	100	87	100	120	100.0
How clear was the audio recording						
Very well	10	30.3	23	26.4	33	27.5
Well	18	54.5	37	42.5	55	45.8
Adequately	2	6.1	18	20.7	20	16.7
Poorly/very poorly	3	9.1	9	10.3	12	10.0
Total	33	100	87	100	120	100.0
Would you like to take another course on mobile phone						
Yes	32	96.97	84	96.6	116	96.7
No	1	3.03	2	2.3	4	3.3
Total	33	100	87	100	120	100.0

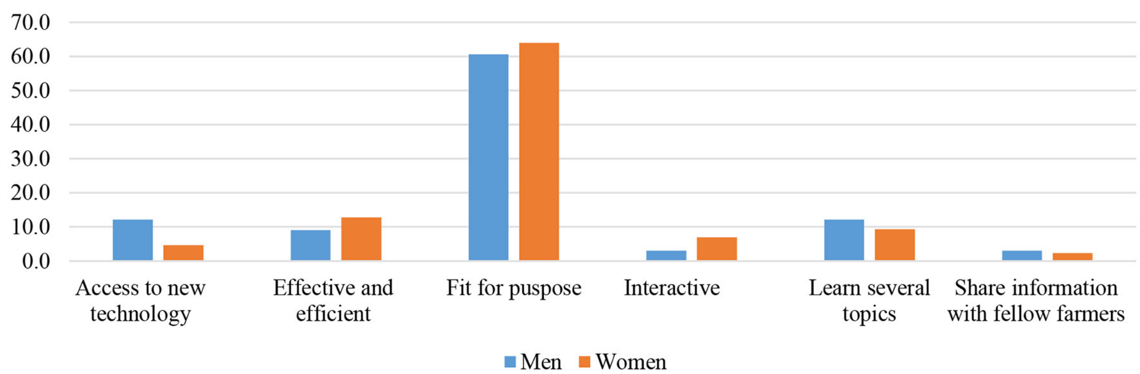

FIGURE 5 | Why would you want more mobile trainings? ($n = 119$).

and technology to farmers that enable them to apply the knowledge directly to improve their farming output and make easy access to market (17). Our study reveals that f2f training methods generated higher knowledge gain than other methods and use of IVR showed a smaller knowledge gain compared to non-IVR for both the trained and non-trained groups. However, a combination of both methodologies yields more knowledge gain. Elsewhere, ICT-based technologies have shown to be very effective in improving knowledge of farmers. That is the case of India where a study concluded that mobile agri-advisory service provided timely and relevant advice to farmers, and farmers adopted new practices based on information received through

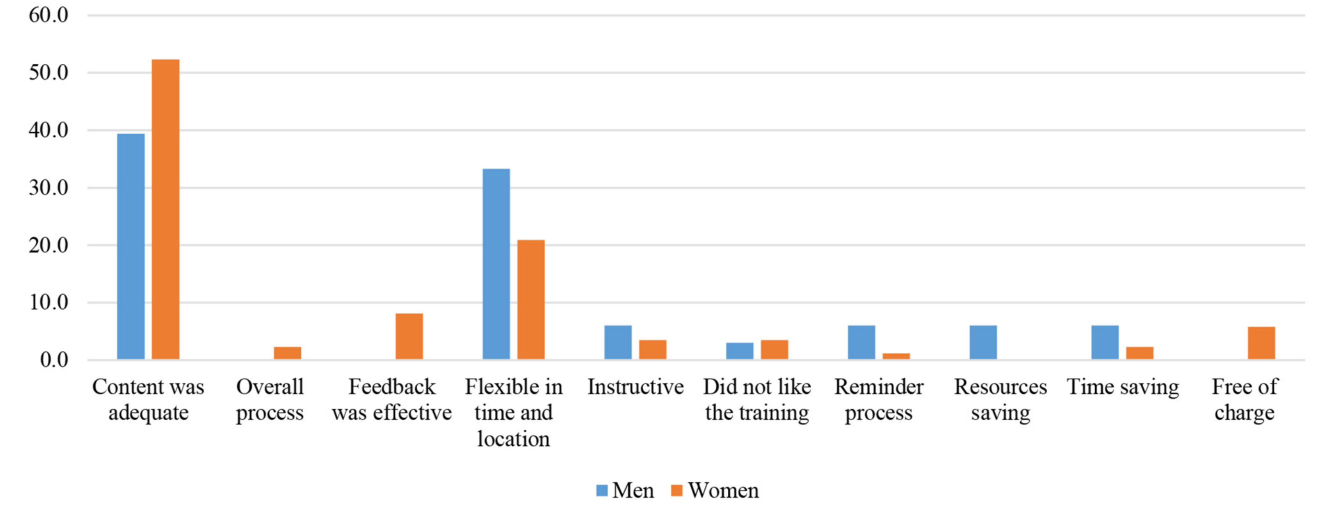

FIGURE 6 | What in particular did you like about the mobile training? ($n = 119$).

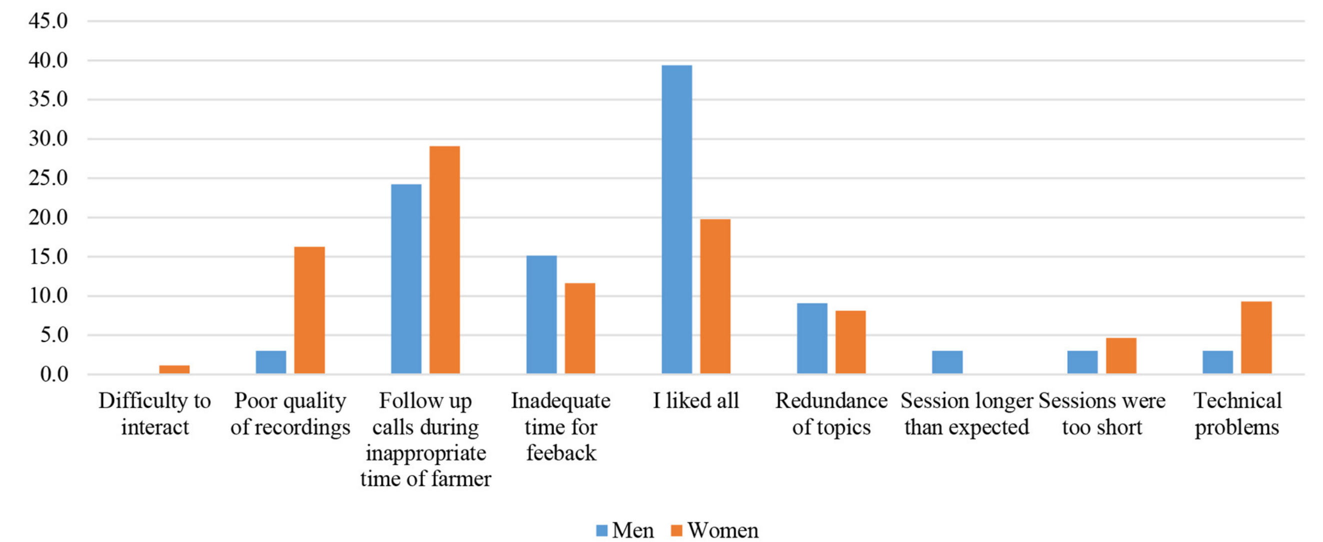

FIGURE 7 | What didn't you like about the mobile training? ($n = 119$).

mobile services (3); the same was also seen in Tanzania (9). The use of mobile phones and emails had a positive impact on farm production of Chilean small farmers (18). However, conservative training (f2f training) still had a higher positive effect on knowledge gain of farmers in our study; this might be because farmers were still used to traditional training. Some farmers experienced technical challenges which limited them from completing the full course. One key thing to note is that the group that only received IVR had a knowledge score of 0.44. Given the short duration of the IVR intervention, there may still have been room to increase this if the intervention ran for a longer duration as the f2f. When combined (IVR + f2f training), the farmer knowledge gain was much higher. These results can be easily interpreted since the objective of the IVR technology was not to replace the conservative training f2f but to augment the delivery of knowledge and information and provide opportunities to farmers to adapt to new technologies that would give them more flexibility for self-learning. Farmer' experience in pig keeping had a negative and statistically significant coefficient in the model. An additional year of farming experienced was associated with a 0.01 reduction in knowledge score. This could probably imply that the knowledge levels of the more experienced farmers did not change much between baseline and endline surveys as they were already knowledgeable about biosecurity practices. f2f training enabled more interaction, but there was no opportunity to get hold of the trainer for further consultation after the training. This gap was filled by the IVR technology whereby the farmers had ample time to consult the services during their adequate time. The IVR system could not avail as much as possible of detailed information as it is the case of the f2f training. This is because the system device has a limit in capacity of information to process. However, there is possibility once the system is set up to add more technical content following farmer demand. While the IVR technology was dependent on power electricity and internet supply and human technical expertise, the f2f training depended on the capacity of the extension services to provide quality human resources to deliver the training, as well as financial capacity to support the field logistics including travels, communication, and meals of both trainers and trainees. Motivating farmers in adoption of new agricultural technologies remained a focal point of the agricultural extension (19). IVR was received by farmers as a new technology capable of transforming their lives since as they said it is time efficient, resource saving, and flexible to timing. ICT-based solutions were also viewed as an enabling tool for extension service delivery targeting poor rural farmers especially women (20). In our study, IVR technology seems to be gender sensitive—most farmers were able to use their own phone and plan the sessions the time they were more receptive without having to seek for approval from their partner, especially for women who are always overburdened with domestic chores and who follow the patriarchal settings of the communities. In this way, IVR technology has the potential to address some gender-related issues which would have raised following f2f trainings, whereby only household heads (most likely men in the study area) tend to attend trainings outside of the home (21). However, there is need for assessment cost development and implementation of both participatory and IVR technologies to better inform long-term investment in extension services by private and public health services.

Limitations of this study include possible spillover of information given that it was impossible to control information sharing among farmers between villages. All interviewers were sourced from the district veterinary office; hence, they are very socially close to the farmers. Therefore, bias associated with the nature of interviewers must also be considered. We expect that on some occasions, farmers gave misleading responses to hide their true perceptions. Farmers volunteered for treatment group, which could indicate a bias toward seeking additional training and knowledge and therefore more likely to increase participation in IVR training.

CONCLUSION

IVR training improved the knowledge of farmers who have never been exposed to training on biosecurity before, and it also had a synergistic effect with f2f training by increasing the knowledge gain of farmers who had also been exposed to the conventional F2F trainings. The farmers who were exposed to trainings using both methods had the highest knowledge gain scores. IVR technology was perceived by farmers as a potential way for relaying information to farmers (time efficient, resource saving, and flexible). It seems to be sensitive since it enabled women to have space for planning their own training. Although IVR significantly increases knowledge of farmers about biosecurity, f2f training remains more effective. Delivery of the technology should be optimized in light of the challenges mentioned to make more positive impacts. IVR could be embedded in traditional extension systems to strengthen conventional training approaches and be used to channel important and urgent information for disease control such as biosecurity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Uganda National Committee for Scientific Technology with approval reference number A508 and by the Institutional Ethical Review Committee of College of Veterinary Medicine, Animal Resources and Biosecurity of Makerere University Uganda with approval reference SBLS.MD.2015. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MD, EK, and ID conceived the study. MD developed the data collection tools. MD and EK collected the data and wrote the first draft of the manuscript. EJP and MD designed the RCT trial. NN and MD analyzed the data. EO and ID made critical review and edits to the final draft. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.611263/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

APPENDIX 1 | Proportion of respondents correctly answering biosecurity knowledge assessment questions (P1—Phase 1, P2—Phase 2).

Variable name	Variable description	P+V+		P+V–		P–V+		P–V–		Overall	
		P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
f45	Housed pigs may not catch ASF	40	47	34	33	40	48	51	41	41	42
f46	Footbath at the farm is a waste of money since it cannot prevent disease	76	97	80	96	92	99	93	96	86	97
f47	If I fence my house, the pigs will not catch the disease (ASF)	51	74	53	54	56	65	59	59	55	63
f48	My pigs can get sick when the traders get close to them	79	99	87	97	76	98	72	94	78	97
f49	My pigs can get sick when the vets get close to them without protective wears	46	37	54	45	43	39	49	41	48	41
f50	Birds or rodents can transmit the disease when they get in contact with the pigs	83	94	88	95	78	99	62	92	78	95
f51	If I isolate the newly coming pigs to my farm, I will stop the disease	79	97	77	96	93	97	94	94	86	96
f52	Pigs will catch the disease if the farm is clean	49	55	40	48	47	52	47	51	46	52
f53	If swill is heated before giving to pigs, chances of catching the disease is reduced	62	96	67	96	84	96	86	92	74	95
f54	Burying dead pigs reduces the disease spread	93	98	87	100	91	100	97	98	92	99
f55	Pigs will not get sick when they ingest offal's from infected dead pigs	83	95	89	96	89	97	88	98	87	97
f56	Un-disinfected farm tools can spread the disease	81	99	77	98	92	95	95	94	87	96
f57	Use of disinfectant is not good for the pigs	86	95	81	97	94	89	99	96	91	94
f58	I should avoid stray dogs from coming close to my pigs because they can transmit the disease to them	94	99	87	98	97	99	98	98	94	98
	Overall	72	85	71	82	77	84	78	82	75	83

APPENDIX 2 | Difficulty and discrimination coefficients.

Item	Discrim/diff	Coef.	Std. err.	z	*P* > z	95% conf. interval	
						Lower	Upper
f45	Discrim	0.31	0.16	1.92	0.06	–0.01	0.62
	Diff	1.13	0.62	1.83	0.07	–0.08	2.35
f46	Discrim	1.18	0.27	4.43	0.00	0.66	1.71
	Diff	–2.37	0.41	–5.85	0.00	–3.17	–1.58
f47	Discrim	0.53	0.18	2.93	0.00	0.17	0.88
	Diff	–0.73	0.28	–2.65	0.01	–1.27	–0.19
f48	Discrim	1.22	0.24	5.07	0.00	0.75	1.70
	Diff	–1.97	0.29	–6.85	0.00	–2.53	–1.40
f50	Discrim	1.37	0.29	4.66	0.00	0.79	1.94
	Diff	–1.81	0.26	–6.89	0.00	–2.32	–1.29
f51	Discrim	1.18	0.24	4.94	0.00	0.71	1.64
	Diff	–2.35	0.36	–6.59	0.00	–3.05	–1.65
f52	Discrim	0.40	0.14	2.81	0.01	0.12	0.68
	Diff	0.14	0.20	0.71	0.48	–0.26	0.54
f53	Discrim	1.70	0.30	5.69	0.00	1.12	2.29
	Diff	–1.45	0.16	–9.16	0.00	–1.76	–1.14
f54	Discrim	2.10	0.43	4.84	0.00	1.25	2.95
	Diff	–2.21	0.23	–9.44	0.00	–2.67	–1.75
f55	Discrim	0.91	0.23	3.96	0.00	0.46	1.37
	Diff	–2.99	0.62	–4.78	0.00	–4.21	–1.76
f56	Discrim	2.21	0.44	5.06	0.00	1.36	3.07
	Diff	–1.71	0.17	–10.00	0.00	–2.05	–1.38
f57	Discrim	1.37	0.29	4.77	0.00	0.81	1.93
	Diff	–2.25	0.34	–6.69	0.00	–2.91	–1.59
f58	Discrim	1.91	0.42	4.52	0.00	1.08	2.74
	Diff	–2.40	0.30	–8.03	0.00	–2.98	–1.81

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A Review of the Evolution of Dairy Policies and Regulations in Rwanda and Its Implications on Inputs and Services Delivery

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The dairy sector in Rwanda plays a key role in improving nutrition and generating income mostly for rural households. Despite the Rwandan 1994 genocide that left around 80% of dairy cows decimated, the dairy sector has experienced significant growth in the past two decades through government, development organisations, and donor programs, and through the nascent vibrant public–private partnership. In this paper, we reviewed and documented the evolution of the dairy policies, programs, and regulations in Rwanda and how they have contributed to the development of the dairy sector. The policy change has impacted the provision and use of inputs and services that have shaped the sector's milk production and productivity, milk quality, and demand. The results suggest that various policy- and program-level interventions have positively contributed to the growth of the dairy sector and improved the livelihoods of low-income households. This has been achieved through increased access to inputs and services, enhanced capacities of the public and private sector to deliver services, strengthened dairy cooperatives' governance, and increased value proposition to members of various farmer groups and promotion of milk consumption. We find that some of the implemented policies and programs, such as the "Girinka" (one cow per poor family) program, Rwanda Dairy Competitiveness Program II, and Rwanda Dairy Development Project, have resulted in improved farmer access to improved cow breeds and improved milk quality and cow productivity through enhanced health inputs and other services. While the dairy policies, programs, and regulations in Rwanda have paved the way for the development of the dairy sector and contributed to the provision and use of inputs and services, there are still challenges that need to be addressed. Accessibility and use of veterinary and artificial insemination services are limited by the quality of veterinary products, while the inadequate quality of feeds leads to low productivity of improved cow breeds. Consequently, farmers' uptake and use of inputs and services can be enhanced through a strengthened capacity of milk collection centres and health and animal feed policies that guide and control the quality of veterinary products and feeds sold in the markets.

Keywords: dairy, policies, regulations, inputs, services, Rwanda

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INTRODUCTION

The 1994 genocide heavily devastated the country's physical, economic, and social infrastructure, yet Rwanda experienced economic growth over the past two decades (1). This growth was led by an ambitious vision 2020, which was the country's long-term framework for development that sought to transform Rwanda into a middle-income country by 2020 (2). Although Rwanda did not achieve all its targeted goals of vision 2020, the country recorded an impressive gross domestic product (GDP) growth of 8% per annum (p.a) that led to an increase in GDP per capita from 211 to 718 USD between 2001 and 2014 and a poverty reduction from 59 to 39% (2, 3). Recognising the importance of the agricultural sector, the government of Rwanda (GoR) increased public investment in the sector and identified the sector as among the key drivers of vision 2020.

Over the past decade, the Rwandan agricultural sector grew at an average rate of 6% p.a (4). The sector plays a significant role in the economy of the country; it contributes about 31% of the total GDP and serves as the country's leading sector toward the achievement of the first and second Sustainable Development Goals (SDGs) of no poverty and zero hunger (2, 5). Furthermore, over two-thirds of Rwanda's labour force are employed in the agriculture sector, while more than 60% of the country's exports are from agriculture (6). Although various subsectors of agriculture have contributed to Rwanda's rapid aggregate growth, the dairy subsector is regarded as the fastest-growing subsector within agriculture as it contributes about 10.5% to the agriculture GDP (7).

Rwandan milk comes from cattle and goats. However, the dairy policies and interventions have been targeting milk from cattle as that from goats is negligible (8). In Rwanda, milk is consumed as raw, fermented (also commonly referred to as "Ikivuguto"), pasteurised, or processed products such as cheese, butter, ghee, and yoghurt (9). The country has three major dairy production systems, namely, zero grazing, open grazing, and semi-grazing (7, 10). Due to land resource scarcity in the country, zero grazing is the most common system in all regions where over 70% of production costs are related to feeds as cattle are kept in a shed and fed on forages. Open grazing is mostly found in Western and Northern highlands where cattle freely graze on individual or communal grazing lands. Semi-grazing is primarily practised in Eastern province, and it is characterised by a mixture of zero and open grazing where cattle are kept in stalls, fed on both forages, and grazed.

The GoR considers the dairy sector as a valuable pathway to economic growth. It not only contributes significantly to the country's total GDP but also offers a means of addressing malnutrition, famine, and poverty to the majority of cattle keepers and service providers along the dairy value chain (DVC) (11). In support of this dual function of the sector, the Rwandan government has been implementing different policies and regulations as well as partnering with various organisations aimed at initiating programs that improve the production and consumption of milk and increase incomes through livestock keeping. In this review, we consider the wide definition of policy by Anderson (12) as a "purposive course of action followed by an actor or set of actors," which means that we consider not only the written government policies but also the actions and programs of various dairy stakeholders and DVC agents that lead to behavioural changes. Most policies and regulations were initiated to support government investments and programs that seek to transform the dairy sector from subsistence to a modern sector.

This paper documents the evolution of the dairy policies, programs, and regulations in Rwanda and assesses their contribution toward the development of the dairy sector, particularly in the provision and use of inputs and services that shaped the sector with regard to milk production and productivity, milk quality, and demand in the country. We also identify gaps that are not addressed by the current policies and the barriers to implementing specific regulations. The findings from this review will ultimately better inform dairy policy and decision making in Rwanda.

Abbreviations: AI, artificial insemination; DBP, dairy best practises; DVC, dairy value chain; FAO, Food and Agriculture Organisation of the United Nations; GDP, gross domestic product; GHG, greenhouse gas emission; GoR, Government of Rwanda; IFAD, International Fund for Agricultural Development; ILRI, International Livestock Research Institute; LMP, Livestock Master Plan; MCC, Milk Collection Centre; MINAGRI, Ministry of Agriculture and Animal Resources; MO, Ministerial Order; NDS, National Dairy Strategy; PPP, public–private partnership; RAB, Rwanda Agriculture Board; RDCP, Rwanda Dairy Competitiveness Program; RDDP, Rwanda Dairy Development Project; RNDP, Rwanda National Dairy Platform; SOQ, seal of quality; USAID, United States Agency for International Development.

MATERIALS AND METHODS

This study comprised a literature review and key informant interviews. We reviewed journal articles, conference papers, reports, and "grey" literature. A wide internet search using search syntax such as [title: (dairy OR milk OR "dairy products") AND (policy OR policies OR regulations OR program* OR "dairy strategies" OR "dairy guidelines") AND Rwanda] OR ab: (dairy OR milk OR "dairy products") AND (policy OR policies OR regulations OR program* OR "dairy strategies" OR "dairy guidelines") was done. We also explored stakeholder websites, including the Ministry of Agriculture and Animal Resources (MINAGRI), Rwanda Agriculture Board (RAB), and Land O'Lakes. Other sites that provided important resources included Heifer International, International Fund for Agricultural Development (IFAD), International Livestock Research Institute (ILRI), and the Food and Agriculture Organisation of the United Nations (FAO). We reviewed 97 related documents, but we considered the information from 35 documents which include 19 journal papers, one book, seven project reports, and eight websites.

To get information on different policies and programs that were implemented, we conducted key informant interviews with 34 different dairy stakeholders in the country. Our key informants included one MINAGRI and two RAB staff, two staff members from Rwanda Agriculture and Livestock Inspection Services, one staff from Rwanda National Dairy Platform (RNDP), one staff from TechnoServe, one staff from

Rwanda Dairy Development Project (RDDP), and a former staff of Rwanda Dairy Competitiveness Program II (RDCP II). Furthermore, our key informants included two board members and one manager from each of the seven Milk Collection Centres (MCCs) located in four different districts (Nyabihu, Ruhango, Rubavu, and Kamonyi) and three staff of an "inyange" milk processor as well as one staff of a milk retailer (fresh dairy kiosk) in Kigali. We also interviewed eight farmers from the four MCC districts to understand the effects of the initiated programs and six consumers to identify different types of milk available to consumers. All our interviews were conducted in-person while taking notes.

We qualitatively analysed this information and used the data from the Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT) to provide a comprehensive image of the dairy sector in Rwanda. Our findings will serve as a basis for further grounded theory on dairy sector outcomes from policy interventions and complement the existing literature on the dairy sector development in Rwanda.

DAIRY POLICIES AND PROGRAMS

Girinka Program "One Cow Per Poor Family Program"

Over the past two decades, the GoR made important gains in rebuilding its livestock sector. After the 1994 genocide, around 90% of small ruminants and 80% of cattle were decimated, leaving the total cattle population at 162,683 in the country (7, 10). From 1995 to 2000, the cattle population started to increase as Rwandan refugees returning into the country came back with cattle. Dairy companies also started operations. In 2006, the GoR initiated the Girinka program, which means "One cow per poor family" to enhance social cohesion and improve family incomes, soil fertility, and nutrition. The Girinka program targeted the households in poverty who then received a dairy cow and were required to transfer the first calf to a qualified neighbour (13, 14). The households in poverty are usually identified using the "ubudehe" system, a comprehensive wealth-ranking system in Rwanda and is embedded into all administrative levels. Households are periodically ranked in their areas on a scale of 1 to 4 according to their poverty or wealth status (where category 1 is the poorest and category 4 is the richest) (7). For a household to benefit from the Girinka program, it must be in category 1 of ubudehe with the capacity to build a cowshed and holding land area between 0.3 ha and 0.75 ha (where 0.2 ha is allocated for cow feed) (13).

The Girinka program's rationale is to improve livelihood and increase nutrition among households in poor households through increased household income, milk consumption, and agricultural productivity (13, 15). It was expected that the given cow produces milk that is consumed by the household, generates income through milk sales, and produces manure that is used as fertiliser in crop fields. Considering that most cattle that were previously kept in Rwanda were indigenous or local breeds, the Girinka program distributed the pure breeds, consisting of mostly Friesian/Holstein and Jersey breeds. Despite the high feed ration demand of these breeds, they were, nevertheless, preferred due to their high milk production and that their progeny from crossbreeding with local cows is compatible with the local environment (13, 16).

The main agencies that have been implementing the program include the MINAGRI and non-government organisations such as Heifer International and Send a Cow. By 2015, around 203,000 households had received cows from the Girinka program, and these beneficiaries constantly receive services such as vaccinations, breeding, and advisory services from public veterinary personnel at subsidised costs (7, 14). Overall, the program has contributed to economic empowerment, poverty reduction, crop production, and improved nutritional status of beneficiary households (15, 17). Furthermore, the total cattle population increased from 645,848 to about 1,350,000 heads between 1997 and 2015, and the crossbreeds increased from 17 to 33%, while the pure breeds increased from 6 to 22% of total cattle between 2008 and 2015 (7, 18).

Rwanda Dairy Competitiveness Programs I and II

The government's investments and efforts to support the dairy sector aroused different investors' and donors' interest in the sector in Rwanda. In 2007, the Rwanda Dairy Competitiveness Program I (RDCP I) was launched and implemented by Land O'Lakes International Development in collaboration with MINAGRI. The 4-year project that aimed at improving the competitiveness of the dairy sector in Rwanda, mostly targeting dairy farmers and the MCCs, ended in 2011 and was funded by United States Agency for International Development (USAID) (19). The project's "push" approach targeted the production side and strengthened the capacity of dairy farmers, giving more attention to farmers living with HIV/AIDS. It enhanced the profitability of dairy farms through increased milk production, improved milk quality at the MCCs, and enhanced the nutritional status of children in poor households and orphans by supporting the government's initiative of a school milk feeding program known as "One cup of milk per child." Furthermore, the project trained about 3,500 farmers living with HIV/AIDS on cooperative management and animal husbandry and assisted in establishing a private Dairy Quality Assurance Laboratory (DQAL) that tests the quality of dairy products (19).

Despite the increase in milk production, the quality of the milk along the dairy value chain was still a concern. Therefore, to achieve the desired high-quality milk, Land O'Lakes, leveraging the momentum of RDCP I, implemented the Rwanda Dairy Competitiveness Program II (RDCP II). The RDCP II project was also funded by USAID and was implemented between 2012 and 2017 with the aim of improving the dairy competitiveness in the region, increasing milk production and consumption, as well as enhancing milk quality (20). The RDCP II was piloted in four milksheds (Northern, Southern, Eastern, and Kigali) covering 17 of the 30 districts of Rwanda. It was expected that quality milk that is produced efficiently and well-marketed throughout the entire value chain would improve the nutritional status of consumers and the income of smallholder producers (3).

In collaboration with MINAGRI, the RDCP II project initiated the dairy "seal of quality" (SOQ) certification scheme, which lays out a set of practises and standards for properly handling raw milk. The SOQ acts as an instrument for achieving the production and supply of quality milk. In this scheme, the dairy players that conform to the standards are given the SOQ certification that lasts for 12 months but is subject to renewal or withdrawal depending on the current compliance of the actors (20). The certification process is administered by the Rwanda Agriculture and Livestock Inspection Services (RALIS), a department under MINAGRI that issues the certificate to the MCCs and small processors who comply with the given standards. The awarded certificate is an intermediary stage that prepares those small processors to aim for the quality marks from the Rwanda Standards Board (RSB). **Figure 1** presents the elements of the SOQ initiative.

The SOQ scheme at the farm level entails many processes that include: hygiene of the milker, cows and milk utensils, animal disease control and veterinary consultations, proper feeding of cows, and milk transport using stainless-steel cans. Furthermore, farmers are required to transport milk to an MCC or to an aggregation point where basic quality tests such as alcohol, lactometer, and organoleptic tests are conducted. The MCCs then distribute the milk to large processors, raw milk sellers, cottage cheese makers, and individual consumers. The milk quality inspection is done at the MCC and at the small processor levels, and it consists of an assessment of hygienic practises, mode of transportation, and milk cooling systems. In addition, a sample of milk is sent to a laboratory to test for somatic cell counts and bacterial counts.

The entry point of the RDCP II project was through the infrastructural improvement of dairy cooperatives and the MCCs in which they could reach out to the members. The project reached out to cooperative members through training in quality feed formulation, use of artificial insemination (AI), veterinary services, and milk handling practises (20). It also partnered with the Rwanda Council of Veterinary Doctors (RCVD) to train the AI technicians to enhance the accessibility and quality of AI services to farmers. The RDCP II encouraged the decentralisation of breeding technology and AI services through private service providers to enhance AI use in rural areas. Furthermore, RDCP II initiated a dialogue with different stakeholders and, in collaboration with RAB and the University of California, Davis, designed a strategic plan for national mastitis control that sought to reduce the occurrence of mastitis in the country (19, 20). In addition, MCC workers were trained on milk handling and quality, and the project supplied the MCCs with milk cooling tanks and milk testing kits, and it encouraged incentive-based pricing of milk using a milk grading system (20).

Upon the end of RDCP II, the MINAGRI changed the SOQ name to "Dairy Best Practise (DBP)" scheme to make it a national scheme and to distinguish it from the SOQ project-led scheme. However, the standards of the SOQ scheme and DBP scheme remain the same. Besides, in line with the policy pillar of the project, some dairy-related policies were implemented through the partnership of RDCP II, MINAGRI, and other stakeholders in the dairy sector. Some of the activities included the design of national dairy strategy (NDS), the creation of the Rwanda national dairy platform (RNDP), supporting the one cup of milk per child program, and a ministerial order to formalise the dairy sector.

National Dairy Strategy

The NDS was a MINAGRI policy document designed and approved in 2013. It identified priorities and approaches to sustainably grow the dairy sector in Rwanda. The NDS was developed in consultation with stakeholders in the public and private sectors; hence, it was considered a roadmap to highlight possible barriers to developing the dairy sector and probable solutions (21). The NDS underlined the needed policies and strategies that would make the dairy sector competitive by providing affordable, accessible, and quality dairy products (21). Furthermore, the NDS emphasised the importance of public and private partnership (PPP) to achieve its objectives of improved production, stable marketing, and required policies that support the dairy sector.

The production objective of NDS was to increase milk productivity at the farm level while maintaining high-quality milk along the value chain. While the pure breeds from Girinka contributed to this, the GoR also invested in accessibility to AI and provision of animal health services and enhanced animal feed production during the dry and rainy seasons (7). This was done by promoting a public–private collaboration that requires private veterinarians and AI technicians to work closely with the MCCs. On the other hand, the marketing objective of NDS was to increase national milk consumption and to formalise the dairy value chain. Therefore, the government and RDCP II project created awareness on nutritional benefits of consuming milk among the population and boosted consumers' willingness to pay for processed milk instead of the unprocessed (20).

Various campaigns, such as *shisha wumva*, which means "feel the goodness" that used different strategies like radio slots, signs, and billboards, were launched, to drive behavioural change and create awareness of milk consumption in rural and urban areas (20, 22). These campaigns supported the already existing "One cup of milk per child" program that the government launched through RAB in 2010. The RAB program sought to address malnutrition among schoolchildren in districts with a high malnutrition rate. Over 83,000 pupils from 112 schools located in 15 districts were enrolled in this program where each child gets a half litre of milk twice a week (23). Furthermore, the government invested in improving rural roads and electrification as well as water supply and encouraged actors in DVC to improve milk value addition that expands milk marketing (7). Through the partnership of GoR and RDCP II, there was a renovation and establishment of new MCCs and dairy cooperatives to facilitate market access and enhance milk quality.

The policy side of NDS was aimed at attracting new investments in the dairy sector and initiating policies that support business transactions and competitiveness. The NDS proposed restructuring of the Rwanda National Dairy Board into the Rwanda National Dairy Platform (RNDP) as an inclusive organisation representing the interests of all dairy stakeholders (21). The RNDP was to ensure the implementation of the NDS

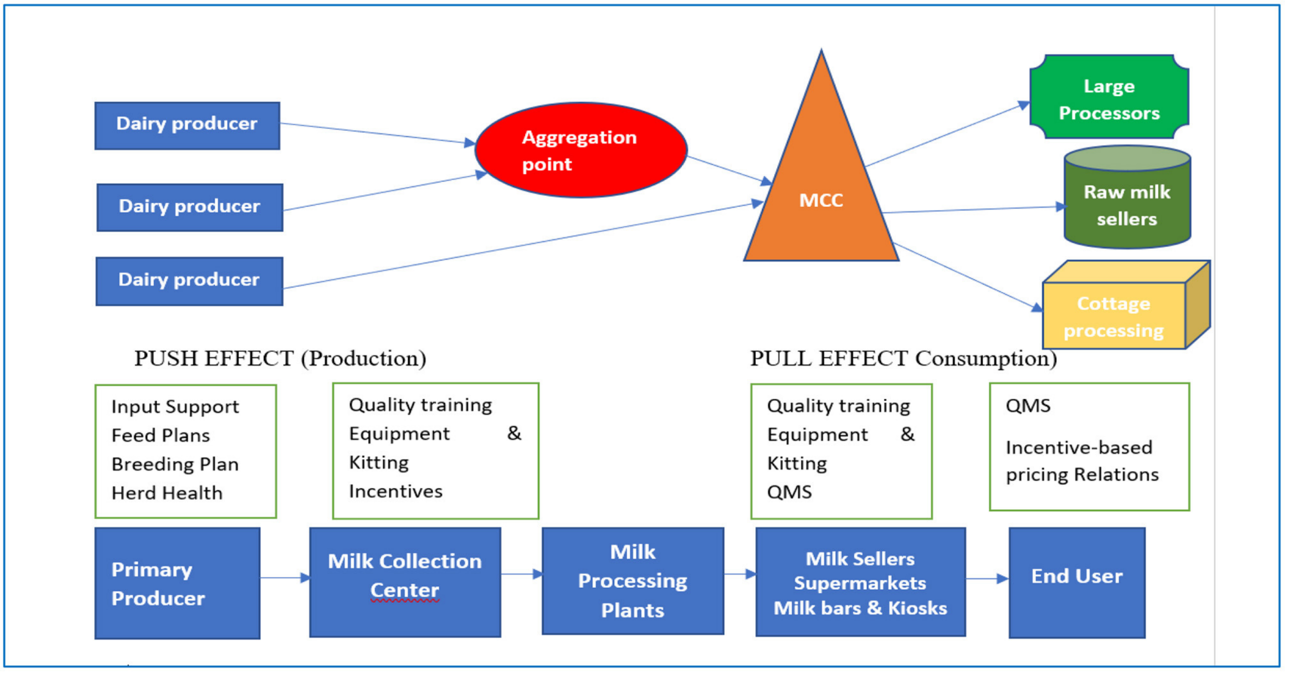

FIGURE 1 | Schematic of the SOQ scheme. Source: Land O'Lakes (20).

and to advocate and promote the interests of all actors in DVC as it was formed based on a strong PPP (20, 21). Furthermore, the NDS sought to increase the trade of dairy products by proposing a harmonisation of tax and trade policies with those of Common Market for Eastern & Southern Africa (COMESA) and regional trade organisations. After meeting the COMESA standards, Rwanda's dairy trade improved, and the country is no longer a net importer of milk but also an exporter (4). While Rwanda has two main milk marketing channels (formal and informal), the NDS proposed a formalisation of the dairy value chain and due support for the SOQ program, which the government later backed through the issuance of a ministerial order (7, 21).

The Ministerial Order

The GoR through MINAGRI issued the Ministerial Order (M.O) No. 001/11.30 of 10/02/2016 that stipulates the guidelines for collection, transportation, and selling of milk in Rwanda. The M.O supports the DBP certification by providing a set of procedures to farmers, milk transporters, MCCs, processors, and milk sellers and whose execution is to ensure that consumed milk is of high quality. The M.O requires that all milk leaving the farm gate should be collected at the MCCs where it is tested for quality prior to being sold. This means that the MCCs must have enough space, cooling tanks, and trained technicians and be equipped with milk quality testing equipment such as alcoholmeter, lacto-densimeter, thermometer, and antibiotic residue and mastitis test kits. Moreover, the M.O requires milk transporters to use well-closed stainless-steel cans or an appropriate vehicle with a cooling tank, while raw milk sellers are required to comply with the cleanliness of related utensils (24).

Despite the M.O's guidelines for formalising the dairy value chain, over 60% of milk is still sold through informal marketing channels in Rwanda (25). Generally, the informal marketing channel is characterised by an unorganised system where milk is not-industrially processed and sold directly to consumers in corner shops, in streets, from farmers, or from vendors, as well as door-to-door, which make the quality of milk questionable as the monitoring process and traceability are difficult (26, 27). Moreover, the informal milk marketing channel in Rwanda is the channel that does not follow the guidelines stipulated in the M.O, while the marketing channel follows the M.O's guidelines regulating the production, collection, transportation, and selling of milk (24). Conversely, the formal marketing channel is well-organised, characterised by legal licencing, and the milk sold in this channel is industrially pasteurised (26, 28).

While Doyle et al. (29) and Reeve (11) argue that the informal milk sector is associated with poor-quality milk potentially causing public health-related risks and diseases, there is a misperception that the milk sold in the informal sector is not automatically unsafe and the milk in the formal sector is not certainly safe (26, 28). This means that eliminating the informal sector based on quality achievement may negatively affect many poor households, mainly on the nutrition of infants and children (28). Therefore, it is prudent to identify the gaps that are yet to be addressed by the current policies and the barriers to implementing specific regulations.

East African Dairy Development Project

The EADD project was a regional dairy sector development program whose phase 1 was implemented in Kenya, Rwanda, and Uganda from 2008 to 2013 and phase 2 was executed in Kenya, Tanzania, and Uganda from 2014 to 2018 (30). The project's aim was to lift farmers out of poverty through increased milk production and marketing (7, 30). The Bill and Melinda Gates Foundation funded the project, led by Heifer International in partnership with ILRI, TechnoServe, the African Breeders Service Total Cattle Management, and the World Agroforestry Centre.

The EADD project involved farmers and supported the initiation of milk hubs operated by dairy cooperatives, where farmers supply their milk for quality testing and chilling before it is sold (30). The project also linked the milk hubs with larger dairy companies and processors for stable milk markets. The EADD project supported dairy farmers in Rwanda by bringing the regional outlook in the country and providing training, and establishing MCCs as dairy hubs (7, 20). Besides the farmers' training on feed and cows' health improvement, the EADD project also trained local veterinarians on the provision of basic services such as vaccinations so that they are easily accessible at an affordable price (30). While the primary role of the MCCs is to provide a market and to ensure that the quality of milk is maintained, they also enhance farmers' access and use of inputs and services. For instance, through the inbuilt check-off system, farmers can access veterinary services and purchase feed supplements and milk cans from MCCs' stores at a lower price even when they do not have cash to pay for them as they are checked off against the milk supplied (30).

Rwanda Dairy Development Project

The Rwanda Dairy Development Project (RDDP) is an ongoing project that was launched in 2016 to contribute to pro-poor economic growth and enhance the livelihood of poor rural households through dairy farming (7). The project seeks to promote climate-smart dairy farming practises and empower women and youth by integrating them into the dairy value chain (7). The project is funded by a concessional loan and grant from the International Fund for Agricultural Development (IFAD), private sector/banks, Heifer International, and the Rwandan government through tax exemptions. The RAB is the leading implementing agency in partnership with Heifer International, the Rwanda Cooperative Agency, the RNDP, the Business Development Foundation, and the Rwanda Council of Veterinary Doctors.

The RDDP has built on the past achievements in the dairy sector and is now concentrating on increasing cattle productivity, milk quality, and processing capacity of the dairy industry and strengthening the policy and institutional framework for the sector (7). This is done by improving farmer proximity to public and private animal health services reinforcing the capacities of public-sector veterinarians and establishing private sector-based networks, comprising animal health workers working under trained veterinary professionals. The RDDP is also focusing on strengthening dairy farmer cooperatives to efficiently provide services to farmers in the form of milk collection and payments and deliver dairy farming inputs to members through bulk purchases. It is also promoting the "hub model" that was successfully tested previously in other countries like Kenya, whereby the dairy cooperatives provide extension, AI, and animal health and financial services either directly or indirectly through linkages with the business development service providers, all geared toward a reduction in dairy market transaction costs (7).

The target of the RDDP is to meet the projected high domestic milk demand and maintain the upward trend in cross-border exports, mostly to the Democratic Republic of Congo and Burundi markets. Although the project is still ongoing, Taiwo et al. (31) found an increase in incomes of RDDP beneficiaries and improved access to extension services and credit facilities. Furthermore, the authors also found that the project has empowered many dairy hubs and dairy farmers' organisations and that, through the Livestock Farmer Field School approach, there has been an increase in the number of farmers able to access inputs and services such as AI, vaccinations, and improved forage seeds.

Rwanda Livestock Master Plan

The Rwanda Livestock Master Plan (LMP) was developed in 2017 by ILRI, with substantial input from MINAGRI, RAB, and other research institutes and universities in Rwanda. Funding support was provided by the Food and Agriculture Organisation (FAO). It is assumed that the livestock sector will positively impact food and nutritional security in the country if the proposed investments are successfully implemented. The LMP is a series of 5-year investment plans for key livestock commodity value chains and production systems chosen based on priority development goals of the GoR. This document presents the visions, targets, challenges, and policy required to achieve the expected outcomes in the government's priority value chains, which include cow dairy, red meat, poultry, and pork (8). The Rwanda LMP is considered as a guiding document to policymakers and all agents engaged in livestock development. The priority investment interventions are meant to meet the agreed national goals, including poverty reduction, achieving food security, increasing economic growth and exports, contributing to industrialisation and employment, and mitigating greenhouse gas (GHG) emissions (8).

To increase milk production to meet the projected increased domestic demand and surplus for export, the LMP presents the dairy value chain development roadmap of 2017/18 to 2021/22. To achieve this, the plan highlights priority interventions in feeds and feeding, animal health, extension services, genetics, processing, and marketing. It also identifies livestock feeds, as the main challenge toward improving livestock productivity and particularly cattle farming (8). Therefore, the LMP proposes the promotion of improved grass and leguminous feed productions in all available areas such as backyards, hedges, and fences. It also recommends creating an industry that produces feed additives and allocation of land for production of improved forage and promotion of the use of concentrates or processed feeds (8).

The priority intervention in animal health highlighted in the LMP is to address the insufficiently trained veterinary personnel and the prevalence of mastitis. Over 60% of cattle in the country have mastitis cases (8). Therefore, the plan seeks to

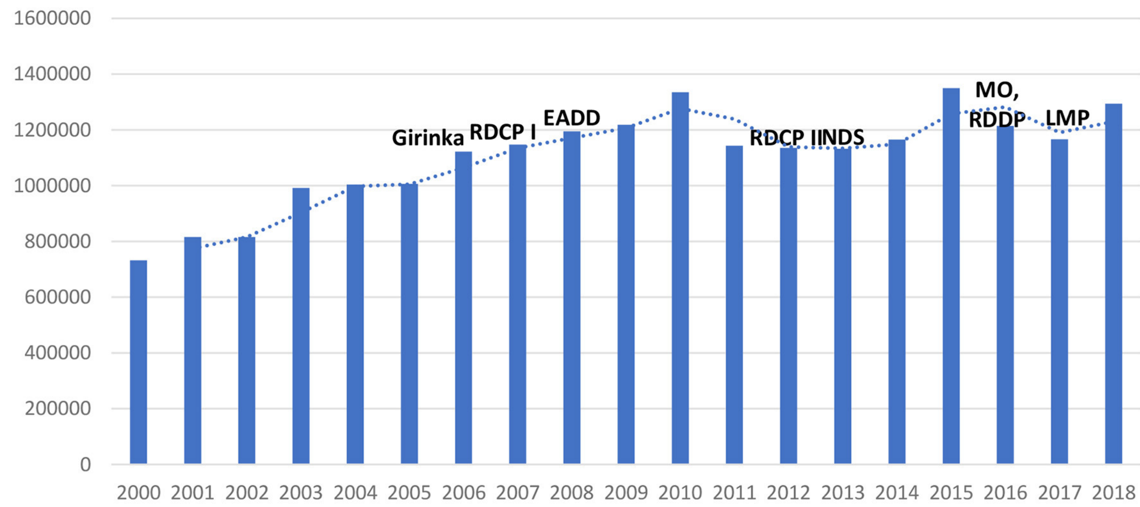

FIGURE 2 | Total number of cattle in Rwanda over time. Source: Based on FAO data (FAOSTAT: http://www.fao.org/faostat/en/#data/QA).

support veterinary diagnosis laboratories, enhance veterinary coverage through PPP, and reinforce disease surveillance and mass vaccination programs' capacity. It projects that by 2021/22, Rwanda will be free from foot and mouth disease (FMD) and contagious bovine pleuropneumonia (CBPP) (8). Furthermore, LMP plans to make vaccines accessible and projects that around 60% of farmers will have adopted mastitis control and management technologies and the recommended rate of tick control treatments by the year 2021/22 (8). Furthermore, the LMP recommends building the capacity of extension agents, providing intensive farmers' training on dairy improvement, and increasing extension service delivery through producer organisations.

Cattle genetics is also the priority intervention in Rwanda LMP where the target is to reduce the local breed while increasing the number of crossbreeds and pure breeds. While the number of local breeds decreased annually at a rate of 4% in the past decade, the LMP's goal is to increase crossbreed cattle by a rate of 8% annually by the year 2021/22 (8). Considering that in 2016/17, only 15% of cows were getting AI services, the training of AI technicians and the promotion of private AI practitioners to make AI service more accessible to rural communities were among recommendations of the LMP. On processing and marketing priority interventions, the plan sets some ambitious goals of establishing around 150 MCCs, 200 milk collection points (MCP), and 150 dairy cooperatives while strengthening the existing ones to fully comply with milk quality standards found in the M.O (8). Moreover, the LMP aims to attain a functional linkage between private milk traders, MCCs, cooperatives, and processing plants so that milk price is based on quality. In addition, the LMP seeks to improve feeder roads to and from the MCCs and enforce the M.O so that around 80% of milk is sold in formal market. These will not only incentivize the establishment of new processing plants but also increase the attraction of local and international investors in Rwandan DVC (8).

DISCUSSION

For the past two decades, several dairy policies, regulations, and programs have been implemented in Rwanda with the aim of improving and promoting the dairy sector, as discussed in the previous sections. Investments in the dairy sector have become financially viable as long as farmers and other DVC actors follow the dairy best practises (32). Undoubtedly, these policies and programs have increased farmers' access and use of different inputs and services, leading to the growth of the dairy sector in the country. Some of the subsequent effects include an increase in cattle population (**Figure 2**), a shift from local breeds to crossbreeds and pure breeds of cattle (**Figure 3**), and enhanced dairy cow productivity in the form of milk volume (**Figure 4**). Furthermore, the dairy sector has been well-shaped as a result of improving different agents of the value chain (**Figure 5**).

An analysis of the FAOSTAT data shows that the total cattle population in Rwanda has increased in the past two decades from about 732,000 in 2000 to ∼1.3 million in 2018 (**Figure 2**). There was a decrease in total cattle population between 2015 and 2017 caused by cattle mortality due to diseases such as tick-borne diseases and Rift Valley fever (RVF) and a prolonged drought experienced during that period (5). Our key informant farmers, who are Girinka program beneficiaries, confirmed that receiving a cow has not only given them access to milk which they were previously unable to purchase, but they also earned some income from milk sales.

Conversely, **Figure 3** shows a significant shift from local cattle breeds to crossbreeds and pure breeds because of the Girinka program implementation and investments in AI services. In 2008, the local breeds represented 77% of the total cattle population in Rwanda, but by the year 2015, the crossbreeds and pure breeds were 33 and 22% of total cattle, respectively. Our interviews with farmers confirmed that every farmer is striving to get a crossbreed or a pure-breed cow. Farmers express their preference for improved breeds due to their high

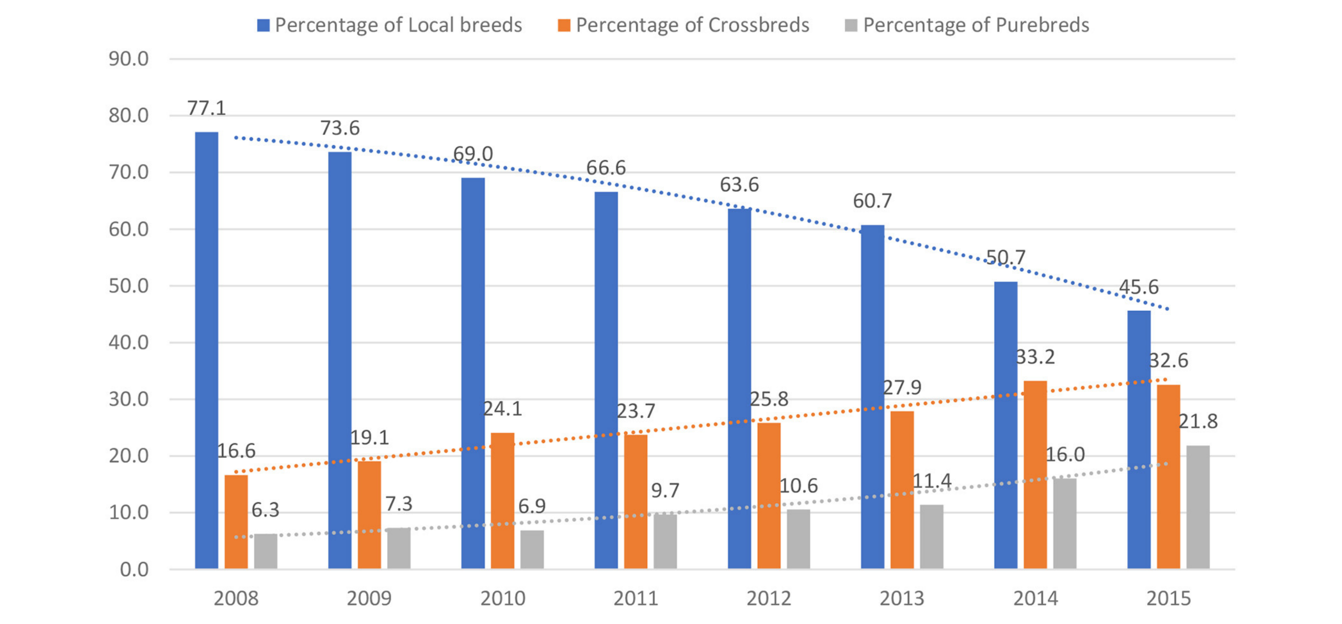

FIGURE 3 | Percentage of cattle breeds in Rwanda between 2008 and 2015. Source: Based on data from IFAD (7).

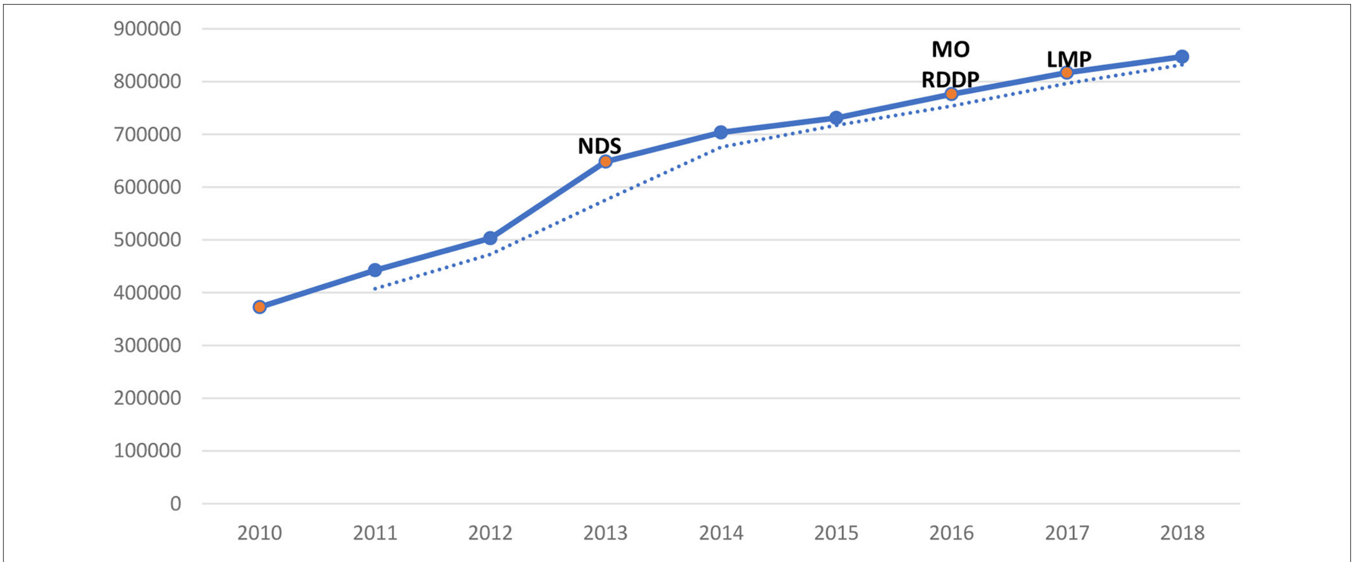

FIGURE 4 | Cow milk production trend in Rwanda in metric tonnes (MT). Source: Based on data from MINAGRI annual report (4).

productivity, longer lactation length, and shorter calving interval. Moreover, those farmers with sufficient finances prefer to buy the crossbreeds or pure breeds, while those with inadequate money use AI or purebred bulls until they get an improved-breed calf.

The interviews with key informants from RAB and MINAGRI attributed the increased milk production to the increase in cattle population and the gradual shift from local breeds to crossbreeds and pure breeds. They argue that crossbred and purebred cows have a higher productivity compared to local breeds when properly fed and if appropriate animal husbandry practises are followed. The MINAGRI annual report of 2018/19 shows that milk production has more than doubled between 2010 and 2018, and milk consumption has increased from 37.3 l per capita in 2010 to 69.4 l per capita in 2018 (4). Although milk consumption per capita is still below the World Health Organisation (WHO)-recommended 220 l per capita per year, the LMP aims to achieve this level by the year 2031/32 (8). **Figure 4** shows a general increase in milk production in Rwanda between 2010 and 2018.

The productivity gains on milk and manure production as well as on improved animal health were realised. Miklyaev et al. (32)

found that daily milk production doubled from 5 to 10 l per cow, which led to an annual increase of milk yield per cow from 608 to 1,949 l in RDCP II coverage areas. It was also established that there was a decrease in the calving interval from 18 to 15 months, a 2-fold manure production at farm level, and a drop in calf mortality from 15 to 10% due to increased feed and adoption of animal health services. Our interviews with RAB and MINAGRI staff corroborate these findings, although they recognised the gap in milk productivity as improved breeds are producing below their potential. They attributed the low productivity to farmers' lack of proper cow management, such as insufficient and/or imbalanced feeds and inappropriate animal husbandry practises.

Increased milk production was realised together with improved milk quality along the DVC, which has enabled the sector to become competitive regionally by meeting the COMESA quality standards (3, 20). The interview with RALIS staff and the MCC key Board Members confirmed that many MCCs have been working with farmers to comply with quality requirements, an element that has reduced the quantity of milk rejected at the MCCs. Whereas, Rwanda has been a net importer of milk, the increased milk production and improved milk quality enabled the country to export surplus milk. In 2018, the country imported 0.118 MT of milk products such as powdered milk and butter, while it formally exported about 4 million litres of pasteurised milk and 1.5 million litres of UHT milk (4). In addition, informal milk exports to Burundi and the Democratic Republic of Congo (DRC) were estimated to be around 15 million litres annually (7). Furthermore, the SoQ expanded the business opportunities to milk agents through existing milk products such as cheese, butter, and ghee that are both consumed locally and exported (20). The Rwanda LMP aims at a 46% increase of crossbred dairy cattle, 65% increase of milk production, and 41% increase of cattle productivity under the recommended level of investment scenario (8). If these targets are achieved, then further policy outcomes will be realised by 2021/22.

While there has been a progressive shift from local cattle breeds to crossbreeds and pure breeds, the interviewed farmers are concerned about the availability of feeds required to ensure consistency of milk supply, especially during the dry season when feeds are insufficient. This is because improved breeds may not attain their potential productivity if they are not fed on balanced feed rations. The implemented interventions have enhanced training on technologies related to conservation of forages for dry seasons, incorporating crop residues and crop by-products as feeds, establishing feed processing plants, and feeding on complementary feed sources (7, 20). Our interview with former RDCP II staff confirmed that the project promoted feed conservation technology such as making silage and cultivation of legumes. However, the MCC board members are worried about the sustainability of these interventions as they require strong support from the private sector to ensure that these inputs are accessible to farmers.

To facilitate milk marketing and processing, the dairy sector in Rwanda was divided into five milksheds, namely, Eastern, Western, Southern, Northern, and Kigali (7). Each milkshed has a big processor responsible for collecting and buying milk from MCCs located in that geographical area. Besides, the MCCs have been empowered through leadership, governance and management training, and enhanced storage capacity. Furthermore, the compliance to the M.O has increased the volumes of milk supplied to the MCCs, which further improved the formal milk marketing channel (20). Despite the role of the milkshed system in providing markets by linking MCCs to processors, it is also disadvantageous to farmers as it limits competition among buyers. This is because processors are only allowed to buy milk from their milkshed. Thus, this system is more beneficial to processors as they buy milk from the MCCs at a low price while the price farmers sell to the MCCs depends on the price the MCCs receive from the processors.

Although farmers are encouraged to adopt better farming practises, farm-gate milk prices are relatively low, where the farmers' share of the final consumer price of milk is 16% compared to international standards of 50% (21). Packaging costs and limited competition among processors are the main contributors to the high price of processed milk (10). Policies geared toward reducing production costs at the upstream channel, including packaging, would reduce the margins between the consumer and producer prices to the advantage of both market participants. At the same time, an expansion of marketing options within milksheds will improve competition from the demand side. Although the "Inyange" processor has invested in milk zones that sell fresh pasteurised but unpackaged milk at an affordable price (20), this system can be upscaled to all districts to easily make this type of milk accessible to the majority of consumers, especially in peri-urban and rural areas. This can be done by introducing milk-dispensing machines (or milk ATMs) as it is the case in Kenya, which require less infrastructure and human resource than milk zones. **Figure 5** below presents the current dairy value chain in Rwanda.

While the dairy sector may be vulnerable to climate change on both the production and marketing sides, it may also contribute to climate change as an increase in dairy production may lead to high GHG emissions if better dairy management practises are not used. Grewer et al. (3) analysed and estimated the effects of RDCP II on GHG emission intensification using the FAO Ex-Ante Carbon Balance Tool (EX-ACT). They found that RDCP II contributed to a reduction of GHG emission intensity (in the project area) by −4.11 tCO_2e per 1,000 l of milk (−60%) and −1.7 tCO_2e per 1,000 l (−47%) in extensive and intensive production systems, respectively. This was achieved through improved feed quality and quantity, herd weights, herd size management, and breeding services (3). Herrero et al. (33) found that low-quality feeds may lead to reasonably high GHG emissions from enteric fermentation per unit of meat or milk due to its low digestibility.

It thus follows that feeding quality forage-based diets supplemented with concentrates and agro-industrial by-products would lead to higher milk production per cow, hence lowering GHG emission per unit of milk produced (34). Similarly, improved animal health and breeding services such as the use of AI decrease GHG emission levels through reduced herd overhead (33, 34). It is expected that Rwanda dairy policies will further

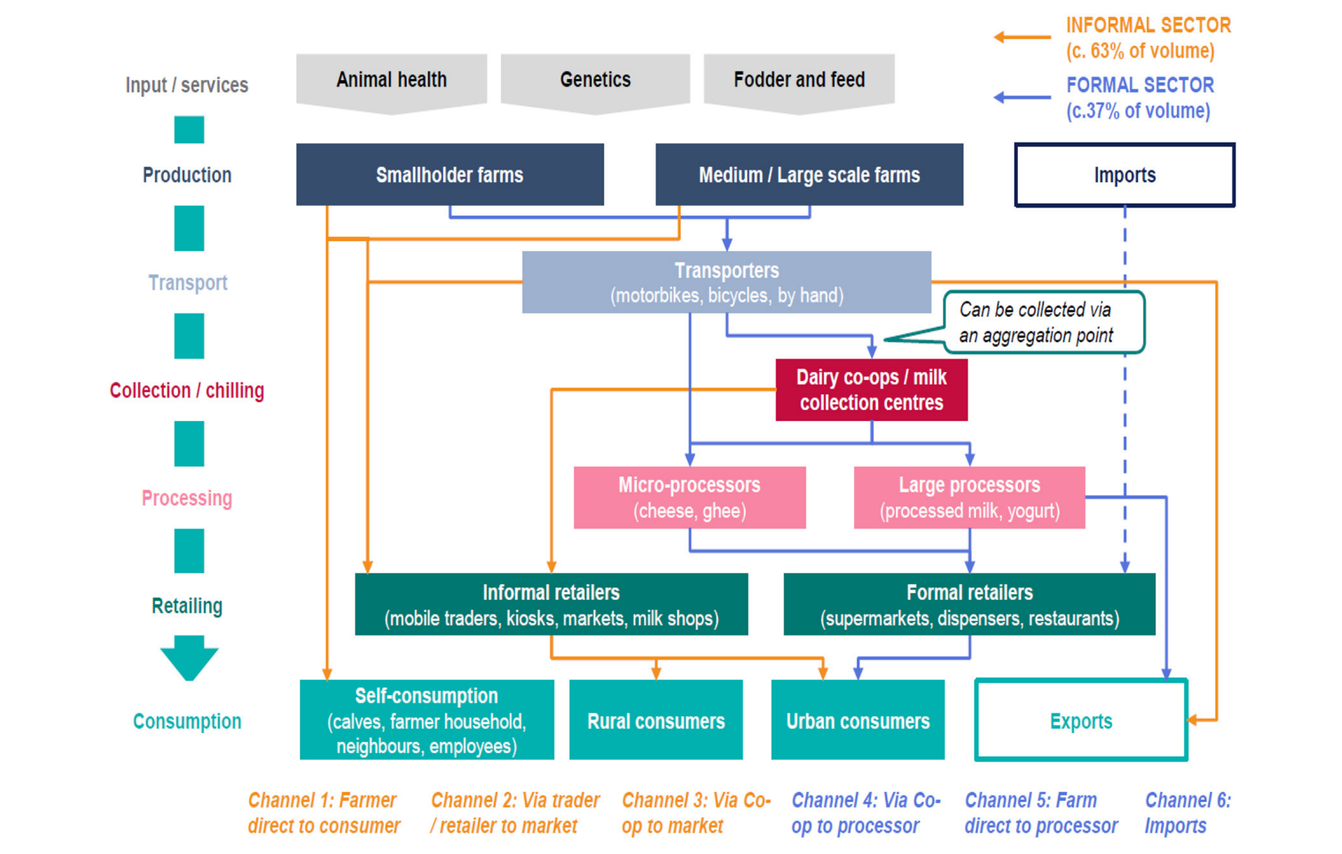

FIGURE 5 | Dairy value chain in Rwanda. Source: TechnoServe (10).

contribute to a reduction of GHG emissions as mitigating the contribution of livestock to GHG emissions is one of the Rwanda LMP objectives (8). Moreover, the ongoing RDDP promotes climate-smart dairy farming (7).

CONCLUSION AND RECOMMENDATIONS

The dairy policies, programs, and regulations in Rwanda have led to an improved dairy sector in the country and contributed to the provision and use of inputs and services. Some of the policies and programs that have been implemented, such as Girinka, RDCP I and II, and RDDP, have enhanced dairy productivity, input market, and milk production through enhanced health inputs and other services. Despite the remarkable growth of the Rwandan dairy sector, the sector still lags behind those of other countries in the region, such as Kenya and Uganda, in terms of milk productivity and consumption (10). There are still some challenges in the dairy sector and barriers to implementing specific regulations. These include the quality of veterinary and AI services, insufficient human resource capacity, low productivity of crossbreeds and pure breeds, insufficient and inadequate quality of feeds, limited competition among milk buyers, informal marketing channels, and insufficient number of MCCs. This calls for strategic investments and more in-depth research that would lead to the formulation of evidence-based policies.

Whereas, accessibility and use of veterinary and AI services have improved, they are still limited by the quality of veterinary products, inadequate human resource capacity, and semen scarcity, while the insufficient and inadequate quality of feeds contributes to low productivity of crossbreeds and pure breeds (9). More policy-driven responses in terms of access to semen and enhancing the number of bull stations are needed, along with health and animal feed policies that guide and control the quality of veterinary products and feeds sold in the markets. It is recommended that a strong PPP that provides adequate youth training on veterinary services, as well as AI technicians to improve farmers' access and use of inputs and services, be initiated and promoted. Furthermore, policies that promote legumes and grass conservation would boost the availability of enough feed from the same land allocated to feed cultivation.

While the MCCs make inputs and services accessible to farmers, the primary concern is that they are still insufficient, and not all established MCCs are well-functioning (7). Therefore, there is a need for designing and implementing policies that provide incentives to the private sector to invest in the establishment of the MCCs across the country and improve their capacity so that farmers can easily access and use the inputs and services. Also, there is a challenge in the transitioning of local breeds to pure breeds or crossbreeds as local breeds still represent 43% of the total cattle population while they only contribute 9% of total milk production in the country (8). Interventions geared toward enhancing the gradual reduction of local dairy cows with improved breeds combined with better management and animal husbandry practises would address the negative correlation between milk production and the number of cattle.

Any policy intervention that seeks to eliminate the informal sector completely may not be successful as it happened in Kenya 10 years ago. Given the failure of the policy, Kenya chose to integrate informal market traders through a training and certification scheme, which ended up improving the quality of milk in the informal sector (28, 35). Incorporating the informal marketing channel in dairy policy formulation rather than its elimination would improve the dairy sector in Rwanda, and other developing countries, where the informal sector is more dominant. This can be done by training and integrating informal milk traders and middlemen to test the milk before they collect it from the farmers as it is the case in the formal sector.

Credible evidence is relevant in lieu of any policy changes. Leksmono et al. (36) highlight the role of research in developing the dairy policy. They found that policy change can easily be realised when the focus is first made on research and development rather than on policy formulation. Therefore, appropriate marketing research may lead to evidence-based policy that accommodates and improves the informal marketing channel. Conducting research on breeds' productivity under different environments would be a useful input to a national breed policy while farmers' adoption of research-based improved forages will address the low productivity of crossbreeds and pure breeds. This study recommends that further farm-level studies are conducted to assess the profitability of better dairy farming practises, given the current policies and more research on dairy projects before dairy policies and programs are initiated.

AUTHOR CONTRIBUTIONS

NH contributed to the conception, design, literature review, conducting of key informant interviews, interpretation of the findings, and drafting of the manuscript. EO, NM, and GO contributed to the conception, design, and interpretation of the findings and drafting and substantive revision of the manuscript. I confirm that all the authors have contributed significantly in the generation of this manuscript.

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Welfare Impact of Community-Based Veterinary and Breeding Services on Small Ruminant Keepers

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Improved breeding practices and participatory health services have been designed and implemented by a partnership between national and international institutions in various parts of Ethiopia since 2014. Based on a panel data of two waves, we have estimated the impact of these interventions on small ruminant fertility, offtake, return per head of animal, and gross income per adult equivalent. Different specifications of the difference-in-differences model revealed that access to small ruminant health services has increased offtake, return per head of sheep/goat, and gross income per adult equivalent. Participants in community-based small ruminant breeding have also higher offtake and gross income per capita than those who are not taking part. The findings of this study are expected to help understand the economic benefits that accrue to rural areas when livestock development interventions are made based on the right diagnosis. The results of this study will also be useful in informing the ongoing discussion in Ethiopia on the transformation of the livestock sector.

Keywords: difference-in-differences, Ethiopia, community based breeding, veterinary services, JEL: C18, C21, Q12, Q13

INTRODUCTION

Livestock are a crucial part of the rural livelihoods in many developing countries where global and local challenges are making the effort to reduce food security and worsen poverty. In Ethiopia, an East African country with an estimated human population of 110 million, rural communities eke out a living from a structurally and institutionally constrained extensive agricultural system. The pastoral and dry lowland parts of the country inhabit communities that depend entirely on livestock for their livelihoods. In the midlands and highlands, crop–livestock mixed production systems are the mainstay of the rural economy. The national herd—consisting of about 55.2 million cattle, 29.3 million sheep, 29.1 million goats, 4.5 million camels, and close to 50 million poultry—sustains, at least partially, the livelihoods of more than 11.3 million rural households (1, 2).

Small ruminants have a multidimensional contribution to the smallholder farmers' livelihoods including economic, social, nutritional, and environmental benefits (3). Subsistence farmers prefer sheep and goats, as the risk of losing large ruminants is often remarkably high (4). Sheep and goats are the best options to improve food security and diversify household livelihood strategies, as they require lower initial capital investment and other production resources such as land and feed. Mainly kept as store of value and as readily available liquid assets, the production and market performance of small ruminants has a clear implication on the financial viability of the smallholder farm households.

The production and productivity of small ruminants have, however, been reported to be low mainly because of poor genetics of the sheep and goat population, high disease incidence and parasite challenges, and lack of feed and forages (5–7). Similarly, the marketing of small ruminants has hardly been rewarding to small ruminant keepers because of inadequacy or absence of market information, market infrastructure, market orientation, and policy support (1).

There have been several efforts to improve the genetics of the indigenous sheep and goat populations (8–10). Nonetheless, sheep and goat breeding strategies in Ethiopia focused on importing exotic breeds. Different governmental (research and academic) and non-governmental institutions and projects implemented these introductions and crossbreeding (11). These programs generated no significant effects on sheep and goat productivity or on farmers and pastoralists' livelihoods and the national economy at large. The major limitations faced have been the lack of a clear breeding and distribution strategy, little consideration of the needs of the farmers and pastoralists, limited or no participation in the design and implementation of the breeding programs, and the lack of schemes to sustain crossbreeds at the village level (7, 11).

Similarly, although there have been decades-old interventions to improve the accessibility and quality of animal health services, the overall achievement has hardly been commendable. Animal diseases affect the livestock population in Ethiopia in many ways including slow growth, low fertility, mortality, and morbidity. The annual loss due to mortality ranges from 8 to 10% for cattle, 12 to 14% for sheep, 11 to 13% for goats, and 56.9% for poultry (12). The major small ruminant health interventions are vaccination and ectoparasite control. Major achievements in vaccination is *peste des petits* ruminants (PPR) vaccination (13). Ectoparasite control efforts were introduced through community-based non-governmental organizations (NGOs) into pastoral areas (14).

The current delivery of animal health services is inadequate both in coverage and in quality. Only 45% of the country is served with animal health delivery systems (12). Alemu et al. (15) argued that animal health research and development interventions tend to deal with animal diseases that affect trade, are transboundary in nature, or are zoonotic. Even though these diseases potentially play a key role in adversely affecting food security and the livelihood of smallholder farmers, little work has been done on endemic diseases, and their contribution to loss of productivity is poorly documented (16).

Since 2012, a new global partnership under the CGIAR's Livestock and Fish Research Program (Livestock Research Program since 2017) initiated and implemented more participatory and local knowledge-based approaches in small ruminant health and breeding programs in Ethiopia. These approaches identified interventions based on comprehensive characterization of the small ruminant production systems in the intervention sites. The interventions involved national partners and individual farmers with the purpose of increasing productivity and financial returns from the livestock (9, 10).

Our research started with the hypothesis that improved veterinary services and breeding practices affect small ruminant fertility and offtake and then improve returns per head of animal and gross income per capita. To assess these impacts, two rounds of comprehensive surveys were conducted in 2014 and 2018. This paper reports the findings of an empirical analysis of the effect of these interventions on selected immediate and long-term outcomes. Using panel data treatment effect models, we report that access to veterinary services improved market participation in terms of increased offtake, income earned per head of sheep and goat, and gross income per adult equivalent. Similarly, taking part in small ruminant breeding programs improved offtake and gross income per adult equivalent. The interventions happened to have no statistically significant effect on the number of lambs/kids per the total number of breeding age does/ewes in a year. The positive effects need to be seen within the context of the crucial role that small ruminants play in the livelihoods of rural communities in Ethiopia.

This study contributes to the relevant body of knowledge in at least three ways. First, we are not aware of any other study in Ethiopia or in sub-Saharan Africa that evaluated the welfare impact of community-based breeding and veterinary services on small ruminant keepers. Given the size of the small ruminant population and the heterogeneity of the production systems in the country, the findings of this study will have relevance to a broader research and development community. Second, we hope that the empirical evidence on the average effect of the community-based breeding and veterinary interventions informs breeders and animal health practitioners on the economic implications of the efforts they are exerting. Finally, the research will also inform policymakers on the importance of and justification for the investment in community-based breeding programs and veterinary services for small ruminants. Considering the insufficient attention given to the small ruminant value chains in the country, this information is expected to help in revising the prioritization of the different livestock development interventions.

MATERIALS AND METHODS

Description of the Interventions

Data-intensive advanced breeding programs or introduction of live animals for cross breeding could hardly be implemented in Ethiopia with the required level of complexity or expected level of success (10, 17). This observation gave rise to a different approach for small ruminant breeding. The novel approach, called community-based breeding program (CBBP) was started in 2009 with four sheep breeds (*Afar*, *Bonga*, *Horro*, and *Menz*) representing different production systems and involving eight communities in Ethiopia (10). These pilot CBBPs have since expanded to include more than 40 communities and have also been introduced to other countries including Burkina Faso, Iran, Liberia, Malawi, South Africa, Sudan, Tanzania, and Uganda. CBBP is a better option compared with the conventional nucleus schemes or importation of exotic breeds in that it is inherently sustainable as it supports local-level decision making, focuses on locally adapted indigenous breeds, and considers the constraints that smallholder farmers face (10, 18). CBBP involves collective action, participatory breeding goal definition and trait identification, breeding male selection, distribution of selected sires and introducing mating management, culling of unselected males, training of farmers, and data collection and management (**Table 1**).

The breeding interventions were undertaken across locations in various parts of the country. Sheep breeding programs have been implemented in *Menz*, *Horro*, and *Doyo gena* districts. Goat genetic improvement interventions were undertaken in *Abergelle* district. *Doyo gena*, *Horro*, and *Menz* represent sheep-dominated production systems. *Abergelle* represents goat-dominated production systems. We combined the two species, and hence, we will refer to the interventions as small ruminant breeding practices. In each of the districts, there are intervention and control *Kebeles*[1]. We considered farmers who were trained and who understood and practiced the different components of the breeding programs in the intervention sites as participants of the improved breeding program.

Animal health interventions were introduced into the study sites as part of the concerted effort to transform the small ruminant value chains. Participatory epidemiological approach (19), was adopted and veterinary health interventions were developed and embedded in the CBBPs. The key assumption behind the choice of this community-based approach is that prevention of selected infectious and non-infectious diseases is less expensive than treating conditions as they occur (20). The design of the interventions was guided by participatory identification and prioritization of the diseases of sheep and goat (15, 21).

The projects districts are *Abergelle*, *Menz*, and *Doyo gena* with adjacent intervention and control *Kebeles* within each district. The health interventions included strategic vaccination for different respiratory diseases, control of reproductive diseases, and deworming for gastrointestinal parasites in small ruminants (**Table 2**) (11, 20, 22). As there are different health service providers in the districts, we considered farm households in the intervention areas who received the services (presented in **Table 2**) only from the formal extension system or the research centers as participants (treatment group) and the rest as non-participants (control).

Sampling

This study used a combination of purposive and random sampling. The study districts were selected with the purpose of developing benchmarks for the interventions of the global research initiative on small ruminant value chain development—which Ethiopia is part of. First off, the intervention and control *Kebeles*[2] were identified. Then, the list of households in the sample *Kebeles* was developed from health service roster or that of taxpayers. Then, we identified households using the lottery method with replacement from each district proportional to the district population size. In total, the study covered nine districts where 1,108 households were visited in 28 *Kebeles*. The sample for the baseline can be considered as representative of the smallholder producers in the country.

The end line survey in 2018 covered only sites where the small ruminant health and improved breeding interventions have been ongoing since 2014[3]. The end line covered *Menz* and *Abergelle* in Amhara Region, *Horro* in Oromia Region, and *Doyo gena* in Southern Nations, Nationalities, and People's Region (SNNPR).

For the end line survey, we talked to the participants and non-participants that we visited in the baseline survey in these four districts. In total, we talked to 571 farm households with an attrition rate of only about 5%. We found 29 observations to be incomplete and, hence, dropped them from the analysis. Therefore, we have a balanced panel of 542 observations for the analysis reported in this article.

The respondents in the survey are household heads or representatives of the household head. We considered fathers and mothers of the house as household heads and talked to whoever was available for the interview. The objective of the study is estimating impact at the household level, and hence the household was the unit of data generation and analysis.

Econometric Framework

We have four outcomes that we hypothesized to be affected by the interventions discussed above. The first outcome is fertility. Fertility is measured in terms of the number of lambs or kids per a breeding ewe or doe in a year. The second outcome variable is offtake measured in terms of the number of sheep or goat sold within a year per household. The third is the average price received per head of animal sold in birr[4] (return/animal). The fourth outcome variable is gross annual household income (income) in birr per adult equivalent (AE).

Estimating the impact of the small ruminant health and improved breeding interventions on our outcomes of interest (fertility, offtake, return/animal, and income/AE) entails comparing the observed outcomes with the outcomes that would have resulted had the smallholders never accessed the interventions. However, the farm households are either participating or not participating, and, hence, we cannot observe both outcomes in the two states of nature (23, 24). Yet identification of the effect of the interventions on the outcome variables requires development of a meaningful counterfactual, i.e., the potential outcome of farmers who participated had they not participated at all.

One of the most common analytical frameworks employed to identify cause-and-effect relationships in a panel data setting is difference-in-differences (DiD) (24, 25). The DiD model is considered as an alternative estimation strategy to deal with possible selection bias by controlling time-invariant differences between treatment and control groups (26–28). In addition, as it can be combined with some other procedures, such as propensity score matching (PSM), the method is a more flexible form of

[1] Kebele [pl. Kebeles] is the smallest administrative unit in Ethiopia.

[2] Kebele, plural Kebeles, is the smallest unit of administration in Ethiopia.

[3] Some interventions were started before 2014, and some sites were added after the baseline survey was conducted. We are reporting only for sites where the baseline survey was conducted and the interventions that followed were informed by the baseline survey.

[4] Birr is the official currency of Ethiopia, and the average exchange rate in December 2018 was 1 birr = 3.6 US cents.

TABLE 1 | Description of the components of the breeding innovation.

Component	Description
• Breeders' cooperatives and controlled small-ruminant mating groups	○ In each site, breeders' cooperative and different mating groups were organized. Cooperatives facilitate regular animal identification, data collection and recording, sire use, and management and rotation among mating groups.
• Definition of breeding objectives and selection traits	○ Identification of the reasons why farmers/pastoralists keep their animals and the attributes they value most is crucial in breeding programs.
• Ranking and selection of best breeding males	○ At the beginning, sires were ranked based on their genetic worth (estimated breeding values) for agreed breeding objective traits and farmers selection criteria.
• Transfer/dissemination of improved sires to the participants and arrange mating system	○ Culling of older/unfit sires and dissemination of new as replacement done once [in the other sites] per year focusing on replacing older sires. This ensures that all flocks have enough and good quality breeding sires to mate their breeding females.
• Awareness creation, field day, and training on small ruminant breeding techniques and capacity development	○ This involves workshop and field days aiming at sharing experiences, and training of participating breeders, extension workers, and researchers. ○ Pregnancy test using ultrasound, fresh semen collection, and artificial insemination started in some of the sites. Field artificial insemination facilities put in place in all CBBP sites.
• Culling and selling of non-selected males	○ Older sires have been culled, fattened, and sold in good price for meat.
• Monitoring and evaluation	○ Data collection and animal identification have been checked and evaluated. Data collected on performances have been analyzed and used to check the genetic progress for traits of interest.
• Certification of improved genetics	○ Breeding sires need to be certified for genetic merit, reproductive performance, and reproductive diseases. This enables dissemination of improved genetics to the base population.
• Establishment of reproductive platforms	○ Establishing reproductive platform was identified to be key for fertility improvement and dissemination. The platform assists in mass estrus synchronization, artificial insemination, and pregnancy diagnosis using ultrasound.
• Development of suitability maps for sheep and goats	○ Mapping breeds/population to suitable environments is important in planning livestock breeding and scaling activities due to its efficiency in allocating improved and new breeds to appropriate habitats for optimal production. In the context of predicting suitable habitats for selected breeds of indigenous Ethiopian sheep and goats, we used geo-informatics based spatial analytic tools to develop breed-specific suitability index maps.

CBBP, community-based breeding program.

TABLE 2 | Description of the components of the small ruminant health intervention.

Component	Description
Deworming SR for gastrointestinal parasites and lungworms	Intended to reduce worm burden in the small ruminant population.
Training farmers on control of SR gastrointestinal parasitosis	Training for farmers on transmission cycles and principles of parasite control
Vaccination for key production diseases	Site-specific vaccination campaigns on ovine pasteurellosis, *peste des petits* ruminants, sheep, and goat pox.
Training of farmers on control of SR respiratory diseases	Training sessions on respiratory diseases and how to control them to ensure vaccinations had the desired buy-in of farmers.

causal inference than other non-experimental methods (29). In this study, therefore, we have employed different specifications of DiD model to estimate the average treatment effect (ATE) on small ruminant fertility, offtake, return per animal, and gross income per adult equivalent of smallholder farmers due to accessing or participating in community-based veterinary or breeding interventions.

DiD estimates the treatment effect based on the data collected from the treatment [accessing/participating] and control [non-accessing/non-participating] groups before and after the intervention. Since the DiD assumes that unobserved heterogeneity in participation is present but is constant over time, it resolves the problem of missing data (unobserved heterogeneities) by differencing out the constant components and provides a more robust estimate of the impact of treatment on participants (25, 30).

The ATE is by definition the difference between the expected values of the differences of the outcomes observed over the two periods conditional on the treatment level. Given a two-period panel setting ($t = 0, 1$), where $t = 0$ refers to before the interventions or baseline and $t = 1$ after the interventions or end line, and the outcome variable for participants is Y_t^p and non-participants is Y_t^n in time t, ATE of the intervention (T) using DiD can be estimated by

$$\delta = E\left(Y_1^p - Y_0^p|T_i = 1\right) - E(Y_1^n - Y_0^n|T_i = 0) \quad (1)$$

where δ denotes DiD and T_i is a treatment indicator equal to 1 if the household is a participant and 0 otherwise.

The DiD can also be estimated within a fixed-effects (FE) regression framework. DiD makes a similar assumption with FE model, but conditions on a group level instead of an individual level effect (31, 32). Following Ravallion (30) and Chakrabarti et al. (26), the DiD model can be specified as an FE linear regression model:

$$Y_{it} = \alpha + \rho T_{i1} + \gamma t + \beta T_{i1} t + \epsilon_{it} \quad (2)$$

where Y_{it} is an outcome measure of household i at time t and ϵ_{it} is the error term, which includes all unobserved determinants of Y_i not included in the model. α is a constant term, ρ denotes specific effect of treatment group (to account for the average unobserved difference between participating and non-participating households which is constant over time), and γ denotes the effect of time FEs. The coefficient β represents the effect of the interaction of treatment and time and hence gives the average DiD effect.

The FE model discussed above is robust to some forms of endogeneity arising from unobservable treatment-specific heterogeneity (31). Specifically, FE models allow covariates to be endogenous provided that they are correlated only with a time-invariant part of the error (33). DiD, as a form of two-way FE model, can control both observed and unobserved heterogeneity (34). More specifically, the outcome variable Y_{it} can be regressed on treatment status T_{it}, a range of time-varying covariates X_{it}, and unobserved time-invariant individual heterogeneity η_i that may be correlated with both the treatment and other unobserved characteristics ϵ_{it}. Hence, the FE model of Equation (2) can be rewritten as

$$Y_{it} = \phi T_{it} + \delta X_{it} + \eta_i + \epsilon_{it} \quad (3)$$

Differencing both sides of Equation (3) over time, one would obtain the following equation:

$$(Y_{it} - Y_{it-1}) = \phi (T_{it} - T_{it-1}) + \delta (X_{it} - X_{it-1}) + (\eta_i - \eta_i) + (\epsilon_{it} - \epsilon_{it-1}) \quad (4)$$

$$\Delta Y_{it} = \phi \Delta T_{it} + \delta \Delta \mathrm{X_{it}} + \Delta \epsilon_{it} \quad (5)$$

Since the source of endogeneity (the unobserved individual characteristics η_i) has dropped due to differencing, ordinary least squares (OLS) can be used to estimate the unbiased effect of the intervention (ϕ). With two time periods, ϕ is equivalent to the DiD estimate in Equation (2) above.

For DiD to yield an unbiased estimate of causal impact, the key assumption of DiD, i.e., the parallel trend assumption, should hold (35). However, it is possible that the initial conditions of intervention and control areas are not similar in terms of some observed and unobserved characteristics in which the subsequent outcome changes might be a function of this difference, which may confound the result (28, 36). The presence of time-varying heterogeneity associated with selection into the treatment groups may cause the parallel trend assumption to be violated and bias DiD estimates (30, 37).

Controlling for initial treatment specific conditions can be used to resolve the effect of time-varying factors that might bias the estimate. In our study, the treatment assignment is not correlated with the error terms of the model. However, the initial conditions may have a separate effect on the changes in outcome as well. We are, therefore, combining PSM and DiD not only to deal with endogeneity that might arise from omitted variables but also to control for all other sources of variation at the start of the study (38). This virtue of combining the two estimators emanates from the fact that PSM is non-parametric, helps balance covariates, and creates a more focused causal inference (25, 30). Hence, using a two-period data of accessing/participating and non-accessing/non-participating groups, the propensity score was used to match participant and control units in the base period, and then the treatment impact was calculated using DiD to the matched sample. Following Guo and Fraser (39), with panel data over two time periods, $t = \{0, 1\}$, DiD estimator for the mean difference in outcomes Y_{it} for each treatment unit i is given by

$$\delta_i = \left(Y_{i1}^{p} - Y_{i0}^{p}\right) - \sum_{j \in c} w\left(i, j\right) \left(Y_{j1}^{n} - Y_{j0}^{n}\right) \quad (6)$$

where $\omega(i,\ j)$ is the weight (based on the propensity score) attached to each control unit j matched to treatment unit i. Hence, to ensure the robustness of the ATE estimates, we have estimated the linear FE and DiD with PSM models.

RESULTS AND DISCUSSION

Description of the Sample Households

We briefly describe the sample households comparing them between intervention and control sites. Our sample was composed mainly [83.8%] of male respondents. The respondents were on average 47 years of age with education of only 1.29 years. Average literacy, in number of years, has slightly gone down in the control sites in 2018, and, yet on aggregate, literacy is higher in control areas than intervention sites. The average household size of the sample respondents was close to six individuals, which is equivalent to the national average for midlands and highlands (40).

The average distance to livestock markets, measured in kilometers [km], is 6.02 for the entire sample. The distance is slightly shorter for the sample in the intervention sites where there is a considerable drop between 2014 and 2018 (**Table 3**). More than 66% of the sample respondents had contacts with agricultural extension agents in relation to small ruminant production. Access to small ruminant-related extension services is lower in control areas even if there is more pronounced leap between 2014 and 2018 in these areas.

Mean comparison between the samples in the two sites over the two waves of survey shows that only the difference in family size is statistically significant ($p < 0.01$) at the baseline level. In the end line survey, however, we noted statistically significant differences around age of the respondent ($p < 0.05$), family size ($p < 0.01$), and average distance from the market in kilometers ($p < 0.001$).

TABLE 3 | Summary statistics of sample households by survey period and treatment status.

Variable	Unit	Baseline [2014]		*N*		End line [2018]		*N*		Pooled			*N*	
		Cont. site	Interv. site		Sig.	Cont. site	Interv. Site		Sig.	Cont. site	Interv. site	Total		Sig.
Gender of respondents (1 = male)	%	87.0	82.2	542		83.3	83.1	542		85.2	82.7	83.8	1,084	
Age (years)	#	44.87 (0.89)	46.06 (0.90)	540	NS	46.91 (0.96)	49.59 (0.86)	542	*	45.87 (0.65)	47.86 (0.63)	47.00 (0.46)	1,082	*
Education (year)	#	1.31 (0.07)	1.29 (0.06)	540	NS	1.22 (0.07)	1.34 (0.07)	541	NS	1.26 (0.05)	1.32 (0.05)	1.29 (0.03)	1,081	NS
Family size [count]	#	6.72 (0.14)	6.22 (0.12)	542	**	6.68 (0.15)	6.16 (0.12)	542	**	6.7 (0.10)	6.19 (0.08)	6.41 (0.07)	1,084	***
Distance to market	km	6.59 (0.39)	6.27 (0.75)	451	NS	6.72 (0.37)	4.86 (0.26)	448	**	6.65 (0.27)	5.55 (0.39)	6.02 (0.25)	899	*
Access to extension (1 = yes)	%	55.2	70.6	542		62.3	73.9	542		58.7.	72.3	66.4	1,084	

Standard deviation in brackets.
$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$, #Number.
Cont. denotes control sites, Interv. denotes intervention, Sig. denotes statistical significance (>0) of the mean difference between control (non-participants) and intervention (participants), and NS denotes not significant.

Summary of the Outcome Variables

There is clear difference between intervention sites and control sites in the initial level of small ruminant fertility rate. The gap, however, remains to be comparable between the two waves (**Table 4**). The other variable with considerable difference between the samples in the two sites is total number of sheep and goat sold over a period of 12 months (offtake). In 2014, the offtake level in control sites is nearly twice that of the intervention sites. In 2018, the offtake in the intervention sites has increased to the extent that it is higher than the level in control sites (**Table 4**). The other outcome variables do not show any peculiar difference over the two periods between the two sites.

Simple mean comparisons show that there were no statistically significant differences between the two groups of farm households in 2018 and over the pooled data. In the baseline, however, the differences between the two groups in terms of total sheep and goat offtake and logarithm of total reported income per AE were statistically significant ($p < 0.1$).

Econometric Results

We report three sets of causality models in this section. The first set is DiD estimations using FE regression with no other covariates (Equation 2). The second set is DiD estimations using FE regression with time variant other covariates (Equation 5). Finally, the third set is combination of PSM and DiD models to control for initial conditions of the sample respondents and compare only those households with comparable likelihood of participation (Equation 6).

The estimation that compares participants and non-participants shows that the access to veterinary services and improved sheep and goat breeding practices significantly increases offtake at the household level. This estimator does not consider any confounding factors and still shows that households with access to veterinary services have supplied six more small ruminants to the market over a period of 12 months. Similarly, farm households who participated in CBBP have on average supplied nine more sheep/goat over a year as compared with those who did not participate (**Table 5**). This model resulted in insignificant cause-and-effect relationship between the other three outcome variables.

Although the intervention and control sites were selected randomly based on a very comprehensive characterization effort (6), we considered, based on theory and econometric criteria, literacy in years of education, family size, and distance to livestock market in kilometers as potential confounders of the cause-and-effect relationship (**Table 6**). This was not however the case, and our estimation simply reinforced the estimator with no covariate reported in **Table 5**. Participating in community-based veterinary services and small ruminant breeding has increased only offtake rates in the project sites.

Finally, we report the DID model estimated on the common support formed based on the propensity score. Treatment effect estimations can be improved through joint specification of DiD and PSM based on pretreatment variables. By combining PSM and DiD, in addition to the unobservable time-invariant characteristics, the observable heterogeneity in the initial conditions can be controlled (25, 30). This estimator also helps in checking the robustness of the impacts observed in the FE models presented above (**Tables 5**, **6**).

The DiD–PSM specification that considered the pre-intervention variables[5] resulted in an enhanced cause-and-effect relationship between participation in community-based veterinary services and small ruminant offtake, revenue per head of sheep/goat, and gross income/AE. Similarly, participation in CBBP has positively and significantly improved small ruminant offtake and gross income/AE (**Table 7**).

Small ruminant keepers participating in veterinary interventions have supplied about 18 more sheep/goat to the market than those who did not participate. These farmers have generated 80.4% higher revenue per head of sheep/goat and 21% more gross income/AE. The farmers who participated in

[5]PSM model results and common support graphs are not reported for brevity reasons. They are available upon request for interested readers.

TABLE 4 | Summary statistics of outcome variables.

Variable	Unit	Baseline [2014]		*N*		End line [2018]		*N*		Pooled			
		Cont. site	Interv. site		Sig.	Cont. site	Interv. Site		Sig.	Cont. site	Interv. site	*N*	Sig.
Fertility rate of the herd	#	25.89 (2.61)	31.34 (2.62)	502	NS	26.98 (2.48)	31.24 (2.38)	518	NS	26.42 (1.8)	31.29 (1.76)	1,020	NS
Total sheep and goat offtake	#	9.31 (1.28)	5.47 (0.92)	526	*	22.66 (1.66)	23.09 (1.31)	519	NS	15.7 (1.09)	14.46 (0.88)	1,045	NS
Ln(return/head)	#	4.42 (0.12)	4.29 (0.21)	107	NS	4.67 (0.08)	4.77 (0.06)	377	NS	4.6 (0.07)	4.69 (0.06)	484	NS
Ln(income/AE)	#	7.69 (0.08)	7.91 (0.06)	542	*	8.19 (0.07)	8.10 (0.06)	542	NS	7.93 (0.05)	8.01 (0.04)	1,084	NS

Standard deviation in brackets.

$^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Cont. denotes control sites, Interv. denotes intervention, Sig. denotes statistical significance (>0) of the mean difference between control (non-participants) and intervention (participants), and NS denotes not significant. Ln(return/head) denotes natural log of revenue generated per head of sheep/goat in birr. Ln(income/AE) denotes natural log of gross annual income per adult equivalent in birr.

AE, adult equivalent.

TABLE 5 | DiD with basic fixed-effects specification without covariate.

	Fertility		Offtake		Ln(return/head)		Ln(income/AE)	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Animal health * Year	−2.56 [−0.44]		5.94** [2.40]		0.54 [1.21]		−0.19 [−1.56]	
Breeding * Year		−5.94 [−1.00]		8.88*** [3.37]		0.27 [0.67]		−0.18 [−1.40]
Year	1.60 [0.48]	0.41 [0.12]	13.47*** [8.47]	13.32*** [8.80]	0.25 [1.00]	0.27 [1.22]	0.44*** [5.07]	0.43*** [5.14]
Animal health	0.99 [0.15]		−5.22** [−2.23]		−0.19 [−0.42]		−0.12 [−0.80]	
Breeding		12.96** [2.00]		−7.78*** [−3.19]		0.24 [0.53]		−0.09 [−0.70]
Constant	28.62*** [9.48]	25.68*** [11.23]	9.12*** [8.84]	9.12*** [11.10]	4.32*** [18.85]	4.23*** [24.44]	7.86*** [119.27]	7.84*** [163.06]
N	1,020	1,020	1,045	1,045	484	484	1,084	1,084
*N*_cluster	544	544	543	543	403	403	547	547
AIC	9,618.5	9,610.2	8,062.5	8,050.5	683.0	681.4	2,167.0	2,168.2
BIC	9,633.2	9,625.0	8,077.4	8,065.4	695.5	694.0	2,182.0	2,183.2

z statistics in brackets.

$^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Model 1 is the animal health treatment effect model. Model 2 is the breeding intervention treatment effects model. Fertility denotes the number of lambs/kids born per breeding female in a year. Offtake denotes the number of sheep/goat sold in a year. Ln(return/head) denotes natural log of revenue generated per head of sheep/goat in birr. Ln(income/AE) denotes natural log of gross annual income per adult equivalent in birr. N is number of observations.

AIC, Akaike information criterion; BIC, Bayesian information criterion; DiD, difference-in-differences; AE, adult equivalent.

CBBP have also supplied 18 more sheep and goat to the market in a period of 12 months. These farm households also earned 20.6% more gross income/AE than did those who did not participate in the breeding program.

In summary, the estimations we made show that participating in the community-based veterinary and breeding interventions improves market participation in terms of supplying higher number of small ruminants to the market. For participants in veterinary interventions, this higher participation is associated with higher return/animal. This is expected, as pests and diseases are among the most important challenges that small ruminant keepers are facing at every level of the production–consumption continuum. In the markets, for instance, one of the insecurities embedded in livestock transactions is the uncertainty around the health status of the animal. Any intervention that ensures the healthiness of the animals will certainly increase the number of animals the farmers raise and bring to the rural markets (1).

Our findings are in line with other positive contributions of animal health services reported in previous research works. Based on a monitoring study that compared infection with strongyle and *Fasciola* species before and after the a community-based intervention, Gizaw et al. (41) reported that the likelihood

TABLE 6 | DiD with basic fixed-effects specification with covariates.

	Fertility		Offtake		Ln(return/head)		Ln(income/AE)	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Animal health * Year	−2.40 [−0.42]		5.96** [2.39]		0.44 [1.18]		−0.20 [−1.60]	
Breeding * Year		−5.38 [−0.90]		8.86*** [3.36]		0.35 [0.91]		−0.20 [−1.52]
Year	1.42 [0.42]	0.37 [0.11]	13.56*** [8.40]	13.43*** [8.76]	0.12 [0.53]	0.19 [0.89]	0.43*** [5.02]	0.42*** [5.12]
Animal health	1.15 [0.17]		−5.71** [−2.37]		0.10 [0.25]		−0.11 [−0.72]	
Breeding		11.68* [1.79]		−8.10*** [−3.33]		−0.04 [−0.11]		−0.06 [−0.49]
Literacy (years)	1.21 [0.36]	0.96 [0.29]	1.64 [1.37]	1.33 [1.08]	0.47 [1.23]	0.48 [1.23]	−0.08 [−1.10]	−0.09 [−1.19]
Family size	1.96 [1.34]	1.69 [1.14]	0.39 [0.78]	0.50 [1.02]	0.32** [2.13]	0.31** [2.07]	−0.07** [−2.43]	−0.07** [−2.33]
Extension on sheep/goat (yes = 1)	2.61 [0.56]	2.18 [0.48]	−0.47 [−0.30]	−0.56 [−0.36]	−0.32 [−1.10]	−0.34 [−1.13]	0.03 [0.40]	0.03 [0.37]
Constant	12.84 [1.10]	12.57 [1.12]	4.98 [1.35]	4.64 [1.26]	1.93* [1.92]	2.05** [2.20]	8.41*** [35.58]	8.37*** [36.97]
N	1,018	1,018	1,042	1,042	483	483	1,081	1,081
*N*_cluster	544.00	544.00	543.00	543.00	403.00	403.00	547.00	547.00
AIC	9,601.63	9,595.10	8,039.33	8,027.65	579.90	587.98	2,152.57	2,154.19
BIC	9,631.18	9,624.65	8,069.02	8,057.34	604.98	613.06	2,182.49	2,184.10

z statistics in brackets.
**p < 0.10, **p < 0.05, ***p < 0.01.*
Model 1 is the animal health treatment effect model. Model 2 is the breeding intervention treatment effects model. Fertility denotes the number of lambs/kids born per breeding female in a year. Offtake denotes the number of sheep/goat sold in a year. Ln(return/head) denotes natural log of revenue generated per head of sheep/goat in birr. Ln(income/AE) denotes natural log of gross annual income per adult equivalent in birr. N is number of observations.
AIC, Akaike information criterion; BIC, Bayesian information criterion; DiD, difference-in-differences; AE, adult equivalent.

of worm infection was significantly lower among livestock after farmers started the collective action for worm control. Admassu et al. (42) similarly observed that there was significant reduction in the impact of diseases handled by community animal health workers (CAHWs) compared with diseases not handled by CAHWs in Ethiopia. Based on simulation study, Beyi (43) reported that milk loss in non-vaccinated dairy herds in Ethiopia was 2.3 and 19.4 times higher than in herds receiving reactive and preventive vaccination against foot and mouth disease, respectively. McDermott et al. (44) and Roth et al. (45) have also reported positive evidence of the returns to investment in brucellosis control, particularly in vaccination of livestock, measured in both livestock productivity and gains in human health.

We also observed that community-based breeding interventions consistently improve small ruminant offtake rates. The higher number of sales is also reflected in the increased gross income per adult equivalent. We have however observed that the return per animal is not statistically different between those who participate in CBBP and those who do not. Yet this is expected as the breeding interventions include identification of the best rams and culling (selling) the ones that do not score high in the traits of interest. In fact, the lack of difference between the participants and non-participants in the breeding interventions could explain the fact that some of the animals are culled at a young age and not necessarily at the right price.

CONCLUSION

International and national partners designed and implemented community-based small ruminant breeding and health interventions in carefully selected sites in various parts of Ethiopia since 2014. This study presents an assessment of the impact of these interventions using two waves (2014 and 2018) of survey data. Different specifications of DiD treatment effects modeling were estimated to investigate the impact of these interventions on sheep/goat fertility, offtake rate, revenue per head of sheep/goat, and gross income/AE.

The different estimations show that veterinary and breeding interventions have significantly increased the number of sheep and goats smallholders supply to the market. The most robust estimator that combined PSM and DiD to control for initial conditions has enhanced the causality between the interventions and the outcomes. Those who participated in community-based veterinary services showed higher offtake, higher return per sheep/goat, and higher annual income/AE. Similarly, those who participated in CBBP managed to sell higher number of small ruminants and earned higher aggregate income/AE.

TABLE 7 | Treatment effect estimated using DiD with PSM.

	Fertility		Offtake		Ln(return/head)		Ln(income/AE)	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Animal health * Year	−0.59		17.53***		0.59**		0.19**	
	[−0.15]		[12.28]		[2.12]		[2.57]	
Breeding * Year		1.16		18.06***		0.49		0.19**
		[0.30]		[12.23]		[1.60]		[2.39]
Literacy (years)	1.21	1.13	0.96	1.20	0.47	0.47	−0.09	−0.09
	[0.35]	[0.33]	[0.70]	[0.87]	[1.21]	[1.20]	[−1.21]	[−1.19]
Family size	1.95	1.97	0.45	0.26	0.33**	0.33**	−0.07**	−0.07**
	[1.33]	[1.33]	[0.81]	[0.46]	[2.32]	[2.28]	[−2.32]	[−2.38]
Extension on sheep/goat (yes = 1)	2.72	2.60	−0.14	−0.04	−0.31	−0.32	0.05	0.05
	[0.59]	[0.57]	[−0.08]	[−0.03]	[−1.01]	[−1.03]	[0.56]	[0.56]
Constant	13.56	13.18	6.37	7.54*	1.95**	2.01**	8.46***	8.48***
	[1.22]	[1.17]	[1.59]	[1.86]	[2.08]	[2.15]	[35.75]	[36.15]
N	1,018	1,018	1,042	1,042	483	483	1,081	1,081
*N*_cluster	544.00	544.00	543.00	543.00	403.00	403.00	547.00	547.00
AIC	9,597.96	9,597.82	8,209.79	8,219.89	577.39	588.07	2,207.63	2,209.50
BIC	9,617.67	9,617.52	8,229.58	8,239.69	594.11	604.79	2,227.57	2,229.44

z statistics in brackets.
$^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Model 1 is the animal health treatment effect model. Model 2 is the breeding intervention treatment effects model. Fertility denotes the number of lambs/kids born per breeding female in a year. Offtake denotes the number of sheep/goat sold in a year. Ln(return/head) denotes natural log of revenue generated per head of sheep/goat in birr. Ln(income/AE) denotes natural log of gross annual income per adult equivalent in birr. N is number of observations.
AIC, Akaike information criterion; BIC, Bayesian information criterion; DiD, difference-in-differences; PSM, propensity score matching; AE, adult equivalent.
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The positive and statistically significant effect of animal health services not only justifies the participatory approach employed in identifying and prioritizing the animal health challenges but also sheds light on to what extent investments on animal health service are rewarding at the community level. The results in this paper shall serve as an additional input to the global appeal for participatory and comprehensive animal health service provision (46–48). Similarly, the results we reported show that the CBBPs designed and implemented by and with the small ruminant keeping community are rewarding in many ways. This is a testament for the argument that introduction of exotic genetic materials is not necessarily the solution for the genetic improvement of the livestock resources of rural communities in Africa or in Ethiopia in particular (10, 49). It is, therefore, imperative to suggest further strengthening and scaling up of the community-based small ruminant breeding programs as long as meaningful financial and economic benefits are to accrue to the society.

We expect the results reported here to inform the national effort that is being exerted in Ethiopia to transform the agricultural sector in general and the livestock sector in particular. Interventions that address the key challenges of the livestock keeping community are crucially important if the livelihoods of the people who depend on their animals are to improve. Proper measurement of the welfare of these interventions helps in prioritizing resource allocation and justifying the interventions at scale.

Finally, we highlight two limitations of our study that can be addressed building on the analytical framework we presented. First, our study covers only sedentary farming systems. Livestock are the mainstay of livelihood in pastoral and agro-pastoral livelihood systems. We anticipate the impacts of livestock services to be more pronounced in these systems. The second limitation is that we focused only on small ruminants. All other species of livestock are equally important in the rural economy of Ethiopia. Broader research will generate empirical evidence that can be used to economically justify prioritization of investments in livestock development across the different production systems.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants, in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

GK led the design, data collection, data analysis, and writing the results of the research. WA coordinated the field data collection during the end line survey and led the cleaning of the data. AH contributed in the designing of the study and writing the research article. TM and SG contributed in writing the research article. BR contributed in managing the entire research program and in writing the research article. All authors contributed to the article and approved the submitted version.

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The Competitiveness of Beef Exports From Burkina Faso to Ghana

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Despite large volumes of cattle stocks in the Sahel, most exports of cattle products remain as live animal sales rather than meat. However, there is increased interest amongst donors and governments to increase value-added exports of beef. In this paper, we provide results from a simulation analysis that explores the prospective competitiveness and benefits of exporting beef from Burkina Faso to Ghana rather than live animals. The paper reviews trading patterns in live animals along the corridor and meat imports from overseas destinations to Ghana. Model results highlight limited competitiveness of the main products demanded in destination markets (offals). Market segmentation strategies, infrastructure development, and animal productivity all generate marginal improvements in competitiveness, but not enough to compete with third-country supplies. Only specific, largely external macroeconomic conditions provide for significant improvements in competitiveness. The paper further reveals the relatively modest employment gains associated with increased exports of meat in lieu of live animals. The analysis suggests a re-think on large-scale investments in downstream functions in the value chain, instead illustrating the fundamental role of upstream investments in productivity, animal health, and collective action to promote greater market integration between pastoralists and formal sector buyers.

Keywords: Ghana, exports, value chain, system dynamics, social accounting matrix, livestock, Burkina Faso

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INTRODUCTION

In West Africa, there has been a recent renewal of the policy debates associated with the promotion of value-added beef exports in lieu of traditional, largely pastoral-based, trade in live animals from the Sahel to coastal West African countries. These pressures have emerged in part from increased pressure and tensions between pastoral and agricultural communities over land and resources that are exacerbated further by climatic stress. At the same time, the increased dynamism of red meat demand along coastal countries in West Africa has driven a number of planned investments in Sahelian countries (Chad, Mali, Niger, Burkina Faso, Mauritania) to develop export-oriented slaughterhouses that ostensibly will enable these countries to capture more of the value-added associated with the production of livestock.

Demand for red meat is expected to remain strong in West Africa. While this provides an opportunity for African suppliers, it could also pose a major threat if issues of productivity, infrastructure, and quality are not addressed. As noted by Hollinger and Staatz (1), the capacity of ruminant livestock value chains (cattle, sheep, goats) to respond to growing demand for red meat is likely to be constrained by low herd productivity due to poor nutrition resulting from seasonal variation in pasture resources and a weak animal feed industry. Poor productivity is also linked to limited investments by farmers on feed, fodder, and other inputs because of low expected returns from undeveloped markets and poor market integration. More generally, low offtake rates coupled with productivity losses due to animal diseases and seasonal feed shortages compromise the long-term capacity of the livestock sector to meet market expectations. Moreover, with growing demand has come increased competition from exports from non-African sources, often at prices well-below what Sahelian suppliers can provide.

In this paper, we examine these issues and opportunities from a simulation analysis that explores the prospective competitiveness of exporting beef from Burkina Faso to Ghana rather than live animals. We combine the use of system dynamics modeling techniques (2, 3) of upstream and downstream marketing and trade of animals and meat in each country with the use of a social accounting matrix to look more carefully at macroeconomic and especially projected employment effects associated with alternative trading models. The paper begins with a review of trading patterns in live animals along the corridor and meat imports from overseas destinations to Ghana. A discussion of the methodology used to assess the prospects of beef exports from Burkina Faso follows, including model assumptions and data used to calibrate the model. We then report the results of our scenario analysis with the model and provide some insights to better interpret model findings.

THE LANDSCAPE OF CATTLE AND BEEF PRODUCTION AND TRADE IN BURKINA FASO AND GHANA

Burkina Faso is one of the largest producers of live cattle in the Sahel. Official statistics of cattle numbers are somewhat dated, but the most recent figures from DGRESS/MRA (4) revealed cattle stocks of just over 9 million head in 2014, growing from 7.6 million head in 2005. Exports of live animals in the same year were estimated at 344,400 (**Table 1**). Some 267,000 head of cattle were slaughtered in the formal sector in 2014, yielding 30,137 tons of beef. Given official statistics that estimate offtake rates of about 12%, this suggests over 479,000 animals are either slaughtered for domestic consumption and/or exported informally.

Movements of cattle between Burkina Faso and Ghana have long been established, with Ghana serving as an important destination market for Burkinabe cattle. **Table 1** illustrates the evolution of this trade as reported by official national statistics on animal trade through 2014. Ghana has historically comprised roughly 35–40% of Burkina Faso's exports of cattle, though this share declined propitiously in 2013 and 2014, due in part to the recovery of the market in Cote d'Ivoire after its political crisis in 2011 and an increase in demand from Nigeria.

Despite long-standing trade patterns in animals between Burkina Faso and Ghana, trade in beef has been negligible. Exports of all meats by Burkina Faso (including but not exclusively beef) in the most recent year available from national statistics for disaggregated trade data (2012) reveal exports of just under 143,000 kg, with sales to Ghana only 738 kg (DGESS/MRA).

While imports of beef from Burkina Faso are a negligible portion of consumption in Ghana, imports from other international destinations are particularly important as Ghana is deficit in red meat. It is instructive to first derive consumption volumes in Ghana to contextualize the scale and nature of these imports. MoFA (5) reports animal stocks in Ghana in 2015 of 1.734 million cattle. Simulation results conducted by the authors using DynMod (6) to project herd dynamics in Ghana estimate domestic offtakes of 153,600 animals, which when combined with past imports (82,700 animals) reported in **Table 1** suggest total animals available for consumption at 236,300 head of cattle based on older data (2014/2015). According to Suleman (7), around 80–90% of imported animals were from Burkina Faso, while informal reports suggest that total volumes of cattle imports by Ghana are around 100,000 animals per year. These figures would imply that up to a third of animals processed in Ghana for consumption are of Burkinabe origin.[1] In Ghana and in West Africa in general, it is further important to differentiate between cuts and offals in understanding consumption patterns, as the latter are highly demanded in the region. Using an average carcass weight of 165 kg (based on an average traded animal of 300 kg and carcass yield of 55%), offals comprising 10.4% of the live animal weight, and World Bank estimates of population (29.5 million), national consumption of domestically processed beef cuts is estimated at nearly 39 million kg, while another 7.4 million kg of offals are produced.

International trade data for beef imports by Ghana are inconsistent, with wide variations in the volumes of imports reported by Ghana and exports to Ghana reported by trading partners in the UN Comtrade database. For instance, in 2017, Ghana itself reported imports of frozen beef (HS 0202 of 3.26 million kg, while total exports of global partners to Ghana in that same tariff code were nearly three times this volume (9.13 million kg). Given that the majority of exporters to Ghana in beef are European suppliers with generally reliable statistics, we use this data to estimate Ghana's imports of beef rather than that reported by Ghana to UN Comtrade. This data is summarized in **Table 2** during the period 2014–2018 for fresh beef (HS 0201), frozen beef (HS 0202), and offals (HS 0206). While erratic, trends in imports by Ghana are rising, with steady imports of offals (over 30 million kg) during this period and rising imports of frozen beef since 2016.

International trade data in meat products do not distinguish between individual cuts in which there can be wide variation in both price and quality. However, implied unit values from individual export suppliers can shed some light on whether imported beef is a primal cut, a low-value cut, a byproduct, or offals. Offals, such as hearts, livers, kidneys, tripe, sinews, etc., are typically priced between US$0.80-US$1.50/kg (f.o.b or c.i.f.

[1] It is likely Ghana imports animals from Mali and/or Niger, but data are not available from these markets.

TABLE 1 | Exports of live animals from Burkina Faso to regional markets, 2005–2014 (thousand heads).

Destination country	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Benin	10.6	16.9	62.4	122.0	73.2	74.9	70.9	33.7	34.4	35.5
Cote d'Ivoire	44.0	37.6	28.9	27.4	33.6	30.4	34.9	26.2	33.5	56.8
Ghana	90.6	125.7	111.5	93.3	85.2	140.0	152.3	136.0	82.0	82.7
Mali	0.8	2.5	2.0	2.8	1.9	1.0	2.1	2.1	1.3	1.1
Niger	5.6	13.9	12.0	17.7	19.9	14.3	11.7	15.3	15.6	33.8
Nigeria	34.9	60.3	118.6	132.3	101.1	83.4	84.4	138.2	140.4	121.0
Togo	17.1	8.2	21.4	13.3	12.6	12.9	15.5	12.7	9.8	13.5
Others	0.6	0.1	0.2	0.6	0.0	0.1	0.0	0.4	0.5	0.1
Total	204.2	265.2	357.0	409.3	327.6	357.1	371.9	364.6	317.4	344.4

Direction des Statistiques Sectorielles, Ministère des Ressources Animales (DGESS/MRA) (4), Burkina Faso.

TABLE 2 | Exports of fresh and frozen beef products to Ghana, 2014–2018.

Year	Fresh cuts (HS 0201)			Frozen cuts (HS 0202)			Offals (HS 0206)		
	Value (USD)	Volume (kg)	Unit Value (USD/kg)	Value (USD)	Volume (kg)	Unit Value (USD/kg)	Value (USD)	Volume (kg)	Unit Value (USD/kg)
2014	65,650	5,593	11.74	9,834,838	7,268,323	1.35	31,783,778	30,627,543	1.04
2015	64,185	11,746	5.46	6,794,863	4,202,084	1.62	32,350,555	36,485,517	0.89
2016	202,560	126,388	1.60	12,573,417	9,660,799	1.30	27,335,381	31,375,020	0.87
2017	315,230	246,277	1.28	13,024,312	9,271,383	1.40	31,884,577	33,369,587	0.96
2018	49,388	27,162	1.82	13,279,098	9,976,993	1.33	37,820,374	34,024,121	1.11

UN Comtrade (updated December 19 ,2019).

depending on product and country of origin). As UN Comtrade data allows the computation of individual supplier unit values for meat exports to Ghana, we can surmise that for beef cuts found in HS 0201 or 0202 where unit values are lower than US$1.50/kg, there is a very high likelihood that such products are some type of by-product and likely sold/consumed alongside offals. In **Table 3**, we provide disaggregated data from 2018 to derive the share of these products in the import basket of beef imports by Ghana. The data often highlight significant variation in unit value depending on the type of cut (or cuts) sold, though the trade data are not sufficiently granular to tease out specific cuts traded. Those imports that are assumed to be by-products are shaded in gray in **Table 3**. Our analysis shows that 98% of the volume of beef imports by Ghana was in the form of either low-value byproducts or offals in 2018; while not reported here, a like analysis of 2017 data shows similar results.

MATERIALS AND METHODS

In this paper, we conducted three types of analyses, using data derived from rapid value chain assessments of the trade and marketing dynamics between Burkina Faso and Ghana (7, 8). First, we looked at price gaps and marketing costs between the two countries to explore baseline competitiveness vs. third countries. Second, and expanding on the first analysis, we constructed a system dynamics model of the trade corridor between Burkina Faso and Ghana to explore the long-term marketing and trade dynamics in live animal and meat markets in each country to assess whether value-added sales of meat from Burkina Faso could be competitive vis-à-vis third markets, and under what conditions/scenarios. Third, to explore the broader macroeconomic and employment effects of these different trading alternatives, we employed the most recent social accounting matrix (2013) of Burkina Faso (9) to run multiplier analyses. The latter two methods are described in detail below in turn.

System Dynamics Model of the Livestock Trade Corridor Between Burkina Faso and Ghana

System dynamics (SD) models are simulation approaches used in the analysis of complex systems. Originally developed in the context of industrial engineering systems, they have been more widely used in a variety of management, ecological, environmental, and social science applications in the last 20 years. SD models move beyond narratives of value chain processes toward frameworks that can provide ex-ante impacts of different investment scenarios associated with technical, marketing, and institutional changes (2). In particular, there could be important feedback effects between the interactions of market dynamics, land use patterns, climate change, institutions, gender dynamics, and socio-economic factors that could

TABLE 3 | Disaggregation of beef exports to Ghana by country of origin, 2018.

Country of origin	Product	Export value (USD)	Export volume (kg)	Unit value (USD/kg)
France	Fresh beef	970	128	7.58
Italy	Fresh beef	6,241	227	27.49
Luxembourg	Fresh beef	2,036	54	37.70
South Africa	Fresh beef	4,584	521	8.80
United Kingdom	Fresh beef	32,427	25,867	1.25
USA	Fresh beef	3,057	356	8.59
Botswana	Fresh beef	73	9	8.11
Belgium	Frozen beef	4,202,168	3,291,955	1.28
Brazil	Frozen beef	516,768	316,789	1.63
Canada	Frozen beef	23,390	2,377	9.84
France	Frozen beef	17,203	3,294	5.22
Germany	Frozen beef	182,664	25,222	7.24
Ireland	Frozen beef	3,379,239	2,798,606	1.21
Italy	Frozen beef	655,974	847,603	0.77
Netherlands	Frozen beef	1,264,554	829,678	1.52
Poland	Frozen beef	523,621	572,447	0.91
India	Frozen beef	641,357	317,000	2.02
South Africa	Frozen beef	316,429	47,322	6.69
Spain	Frozen beef	166,833	33,381	5.00
United Kingdom	Frozen beef	1,067,253	844,544	1.26
USA	Frozen beef	289,259	16,475	17.56
Kenya	Frozen beef	20,627	2,300	8.97
Ukraine	Frozen beef	11,759	28,000	0.42
Argentina	Offals	327,316	318,763	1.03
Austria	Offals	31,495	25,600	1.23
Belgium	Offals	4,730,824	3,806,161	1.24
Brazil	Offals	5,039,315	3,650,443	1.38
Croatia	Offals	77,479	125,000	0.62
Cyprus	Offals	22,699	24,660	0.92
Estonia	Offals	29,142	78,000	0.37
France	Offals	484,377	226,367	2.14
Germany	Offals	2,649,137	3,579,817	0.74
Greece	Offals	13,762	24,807	0.55
Iceland	Offals	75,490	98,780	0.76
Ireland	Offals	8,114,371	6,761,650	1.20
Italy	Offals	2,954,252	3,229,267	0.91
Other Asia, nes	Offals	3,746	5,400	0.69
Netherlands	Offals	6,619,382	5,387,134	1.23
Norway	Offals	228,685	248,530	0.92
Paraguay	Offals	84,837	83,997	1.01
Poland	Offals	742,650	904,017	0.82
Russian Federation	Offals	854,487	1,053,160	0.81
Serbia	Offals	76,538	126,580	0.60
South Africa	Offals	2,233	457	4.89
Spain	Offals	1,614,992	1,499,750	1.08
Sweden	Offals	86,789	101,000	0.86
United Kingdom	Offals	2,795,969	2,463,223	1.14
USA	Offals	144,800	174,058	0.83
Ukraine	Offals	15,607	27,500	0.57
TOTAL IMPORTS		51,148,860	44,028,276	1.16
Total low value cuts		11,136,995	9,238,700	1.21
Total offals		37,820,374	34,024,121	1.11
Percentage of low value cuts and offals in total imports		96%	98%	

UN Comtrade; shaded figures denote low value cuts. See text for details.

influence the uptake and success of any proposed intervention that traditional economic methods or statistical analysis may not pick up or lack local level data to rigorously analyze. In the context of beef trade, such models have been applied in a number of previous analyses including (10) which assessed the viability of a proposed two-stage export certification process in Ethiopia using quarantine stations and feedlots to ensure disease-free status and higher quality of beef for export to markets in the Middle East; a study on commodity-based trade and export feasibility from communal areas of Namibia (11); and an analysis of reforms to improve competitiveness in the beef sector in Botswana (3).

System dynamics models are a set of non-linear differential equations that utilize a graphical programming structure to represent system behavior. They employ core concepts of stocks, flows, and feedbacks in modeling non-linear systems. Stocks represent an accumulation of tangible or intangible goods at time *t*. Flows represent the rate of change of a stock. The net level of a stock changes through flows, either from an inflow into the stock or an outflow out of it. Flows are mediated by parameters which can be a combination of numbers, equations, or graphical functions that regulate the rate of change of inflows or outflows. Feedback denotes the dynamic behavior of a system induced by combinations and interactions of stocks, flows, and parameters. Feedback loops that are reinforcing magnify change in a system, causing either exponential growth or delay, whereas balancing feedback loops converge onto a steady state. SD models typically combine a set of reinforcing and balancing loops. While qualitative archetypes can deliver some intuition about the behavior of simple interactions between combinations of feedback loops, computer simulation is necessary for more complex models (12).

The system dynamics model used in this analysis integrates a herd model of animal population dynamics in each country combined with trade dynamics of live animals given excess supply in Burkina Faso and excess demand in Ghana. Downstream, sold animals are then further processed into low-value cuts, high-value cuts, and offals in each market with sales of each depending on consumer demand. Imports of offals into Ghana are also modeled. In **Figure 1**, the interactions of the different modules of the model are provided. Herd population growth in each country determines the volume of trade in each period, which in turn specifies the price at which trade takes place given excess supply and demand for animals based on the demand for meat in each country. These prices in turn influence the decision of farmers in each country to sell or retain animals in subsequent periods. They also determine how much is traded with other West African countries and, in the case of Ghana, demand for imports from third countries. The specifics of each of these modules is discussed in turn below, with core modules and model equations found in the **Supplementary Materials**.

The herd model quantifies the supply of animals available in each market. The herd model is based on DynMod (6), a model developed by CIRAD and ILRI to examine the evolution of herd growth based on parameters of herd demographics, birth and mortality rates, and offtakes for sale. Animals in the herd model are divided into demographic cohorts (juvenile animals, sub-adults, and adults) split by gender; each cohort is represented as a stock in system dynamics. Flows between stocks depend on a set of fixed transition probabilities associated with survival and whether an animal is sold or purchased. The herd model used in this application extends that of Lesnoff (6) in two ways. First, we make offtake rates in both countries price-endogenous to account for supply response based on price changes. We apply a simple double-log functional form with the probability of sales a function of the live animal price. Given that livestock are both consumption (i.e., through their sale) and production (i.e., as inputs for breeding) goods (13), we differentiate our price responsiveness based on age/sex cohorts[2]. For male animals, we assumed elasticities of 0.05 for juvenile animals and 0.1 for sub-adult and adult males, with price elasticities of supply set in proportion to the frequency of sale. For female animals, juveniles are not sold so we set an elasticity of zero for this cohort. Sub-adult females were assumed to have an offtake elasticity of 0.05, while adult females, used for breeding, have an offtake elasticity of −0.05. The latter implies that an increase in price reduces the number of adult females sold so as to breed more animals in future. These low supply elasticity assumptions align with other estimates of live animal figures [see (14)]. Second, we model seasonal offtakes directly based on data reported in Ouedraogo (8). In the original DynMod model, monthly offtake rates are assumed constant and annualized to simulate herd trends on an annual basis. In this version, as the system dynamics model is run on a monthly-time step, we can directly apply a monthly seasonal trend to our price-endogenized offtake equation based on trading patterns from Burkina Faso to Ghana during 2015–2018 (**Figure 2**).

Net animal offtakes from both countries (representing supply), combined with derived demand for animals based on meat production, define the volumes of animals traded and their price based on an equilibrium relationship between excess supply from Burkina Faso and excess demand from Ghana; in international trade parlance, this is analogous to using a "three-panel" graph [see (15)]. For simplicity, residual live animal sales from Burkina Faso to the rest of West Africa are based on a simple demand function calibrated to derived demand and income growth for Cote d'Ivoire. While Nigeria is an important destination market, a lack of data and fairly stable macroeconomic policy (exchange rate fluctuations) since the large depreciation in 2016 motivated our use of Cote d'Ivoire as a proxy.

The module of live animal trade follows the approach of Sterman (16) which uses inventory relationships to calibrate live animal excess supply and excess demand. System dynamics models of supply and demand derive price and quantity relationships based on the gaps between actual and desired inventory levels, which in turn drive whether prices rise or fall in a particular period. For instance, if actual inventory is greater than desired inventory, this causes pressure to liquidate inventories and reduces the traded price. These prices are

[2]Initial offtake rates based on (6) are 0.1 for juvenile males, 0.2 for subadult males, 0.21 for adult males, zero for juvenile females, and 0.05 for subadult and adult females based on a generic West African herd profile.

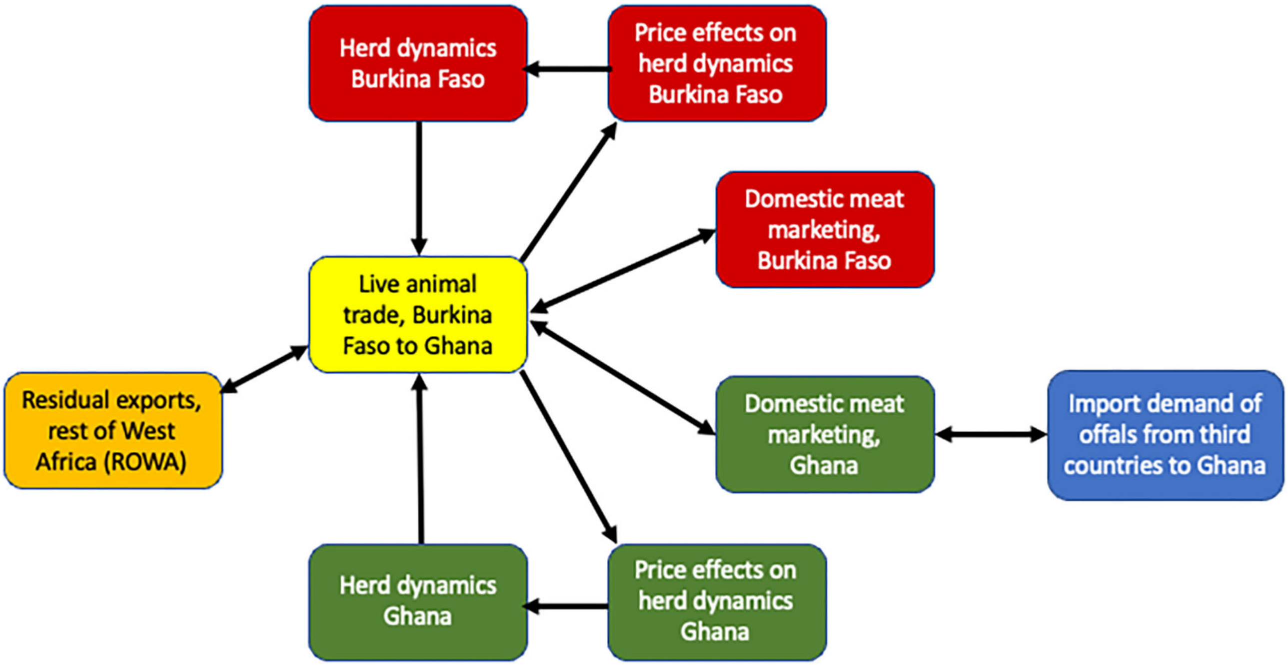

FIGURE 1 | Modules of the simulation model.

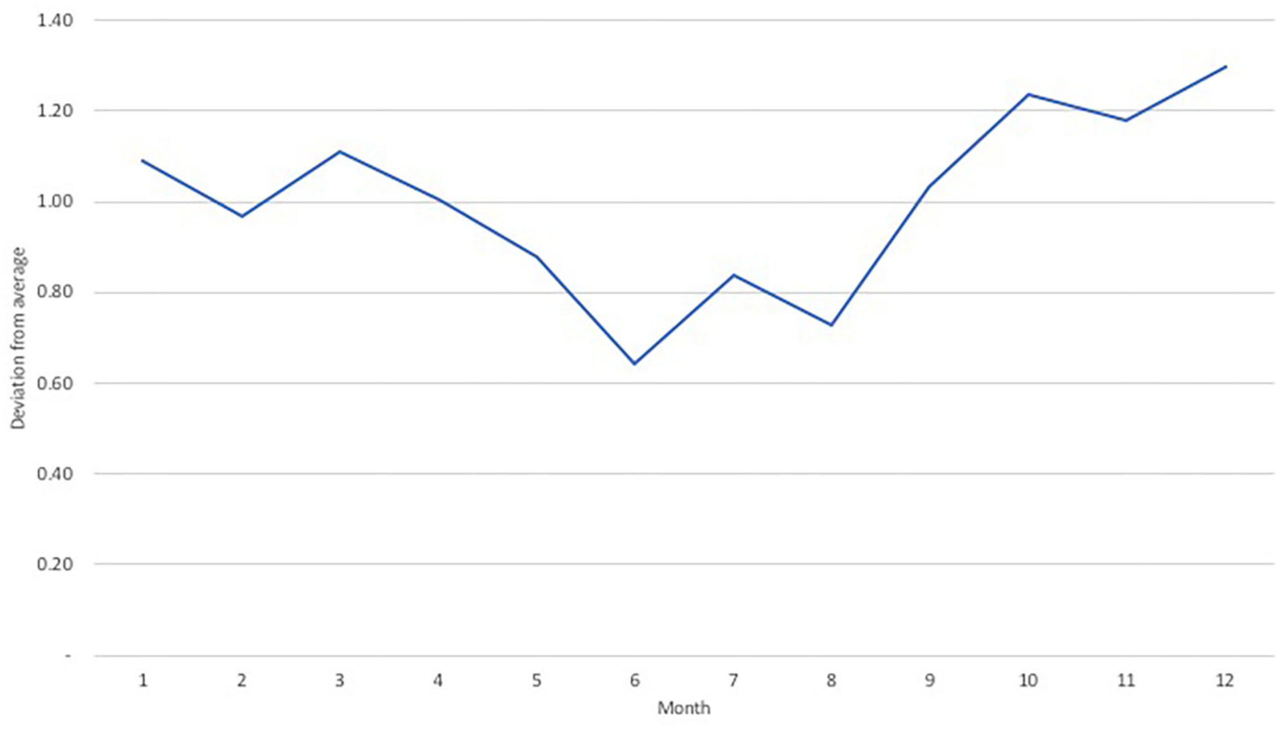

FIGURE 2 | Average seasonality of animal offtakes from Burkina Faso to Ghana, 2014–2018. Ouedraogo (8).

transmitted to the model's live animal supply and derived animal demand (marginal cost of meat) functions which then (in the next period) determine a new set of inventory relationships that set subsequent prices (16, 17).

In downstream meat markets, we adopted a long-standing model of joint product pricing under monopoly as first characterized by Colberg (18) in general settings, and Ciriacy-Wantrup (19) in agriculture. This model has been further analyzed by Houck (20), Jensen (21), Manes and Smith (22), and more recently by Shastitko and Shastitko (23), while Piggott and Wohlgenant (24) applied this framework in an international trade setting.

We consider a model of monopoly given that formal sector processing of beef in West Africa tends to be dominated by a very small set of actors (mainly in capital cities) whose actions influence the prices of other informal actors. The motivation for using a monopoly assumption is to address the market power that larger, formal actors have to set prices for animals and meat, which are then transmitted and adopted by smaller, informal actors in both countries. Previous research by Sesay (25) has noted that butcher associations in West Africa typically act as monopolies, and public intervention, particularly downstream in the livestock value chain, has been commonplace. Production and marketing data further bolster this argument. In Burkina Faso, for instance, according to the most recent year (2014) of livestock sector statistics, sales of live animals to the Ouagadougou abattoir averaged 195 head of cattle per day. Assuming 300 days of throughput, this yields 58,500 cattle processed annually, or 6,611 tons of meat [based on a reported 113 kg/animal carcass weight from Ouedraogo (8)]. National statistics further reveal some 102,400 animals were slaughtered in registered slaughter facilities in Ouagadougou in 2014, suggesting that over 57% of animals pass through the main slaughterhouse. In the Accra area of Ghana, Suleman (7) reports that 40% of daily cattle slaughter occurs at the main Accra slaughterhouse. These figures suggest some degree of market power by the main slaughterhouses which justify deviating from a perfect competition assumption. We recognize that while meat processing does not operate as a pure monopoly, neither does it exhibit perfect competition and that a monopoly assumption is a more realistic representation of the actions taken by larger entities with pricing power. An oligopoly representation would be an alternative means of looking at meat markets, though we did not have data to model issues of strategic interaction between firms; this is an area for future research.

The basic model is presented in **Figure 3** whereby a monopoly produces two products (here, H denoting high-quality beef and L denoting low-quality beef) in fixed proportions and whereby the marginal costs between them cannot be allocated between their production. In such a model, the monopolist produces where the sum of marginal revenue equals marginal cost, with prices in each market where such quantity intersects the respective demand curve.

An important consequence of this model, as denoted in **Figure 4**, is the implication of a change in demand in one of the two products. A shift in the demand curve of H to the right induces a shift of total marginal revenue to the right, causing a rise in the price of H and a fall in the price of L (see the left-panel in **Figure 4**). Much of the analysis in the articles cited above study the implications whereby such a shift is large enough to cause a glut in the low-value product (L) by virtue of producing where MR_L is negative, meaning that a portion of L would be thrown away to maximize monopoly profits.

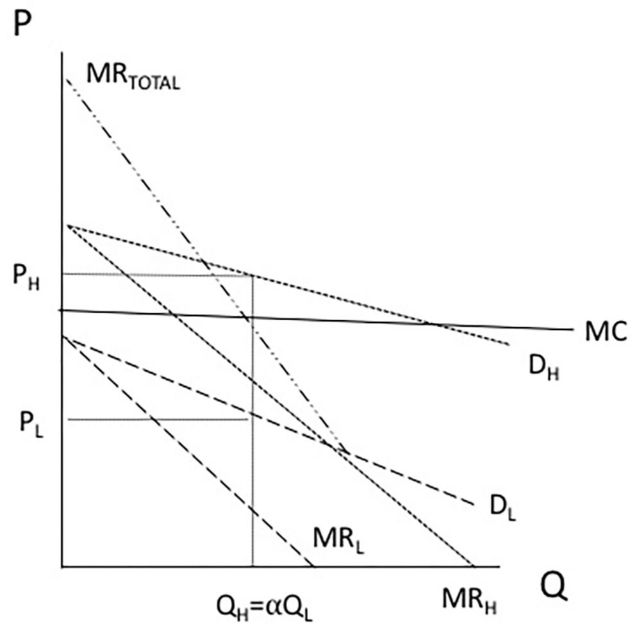

FIGURE 3 | Pricing of joint products under monopoly pricing. Adapted from (18).

Our focus with this model is not to consider issues of gluts, but rather to consider the potential tradeoffs that might exist in pursuing higher-value markets. **Figure 4A** indicates that greater product differentiation would provide more pricing flexibility for L relative to the status quo, but only if the marginal costs of targeting new markets do not change. In **Figure 4B**, we illustrate that a combination of a shift in demand and a rise in marginal cost to meet such demand may raise the price of the lower-value product, and reduce the pricing flexibility that a monopolist might have. Should scale economies result from greater efficiencies in production that offset the rise in SPS costs, it is possible that marginal costs could fall, providing an opposite effect as that illustrated in **Figure 4B**.

In the case of Ghana, we also assume the import of offals from third countries. We modeled a simple import demand curve of offals that is a function of the world price of offals, the domestic price of offals, and income. We assume imperfect substitutability of domestic and foreign offals, as the former tend to be fresh and the latter frozen. World prices were assumed to exogenously grow by 2% per year based on the compound annual growth rate of price changes for offals from **Table 2** over 2014–2018. We also modeled a modest exchange depreciation of the Cedi against the U.S. dollar and CFA (5% for each), which is lower than the average over 2009–2017 (16% against the USD, 13% against the Euro (CFA).

The model was run monthly over a 10-year period to simulate how herd dynamics influence marketing dynamics, given assumptions on income and demand growth, and to see what options (if any) exist for trade in beef products from Burkina Faso to Ghana. As a system dynamics model, the model

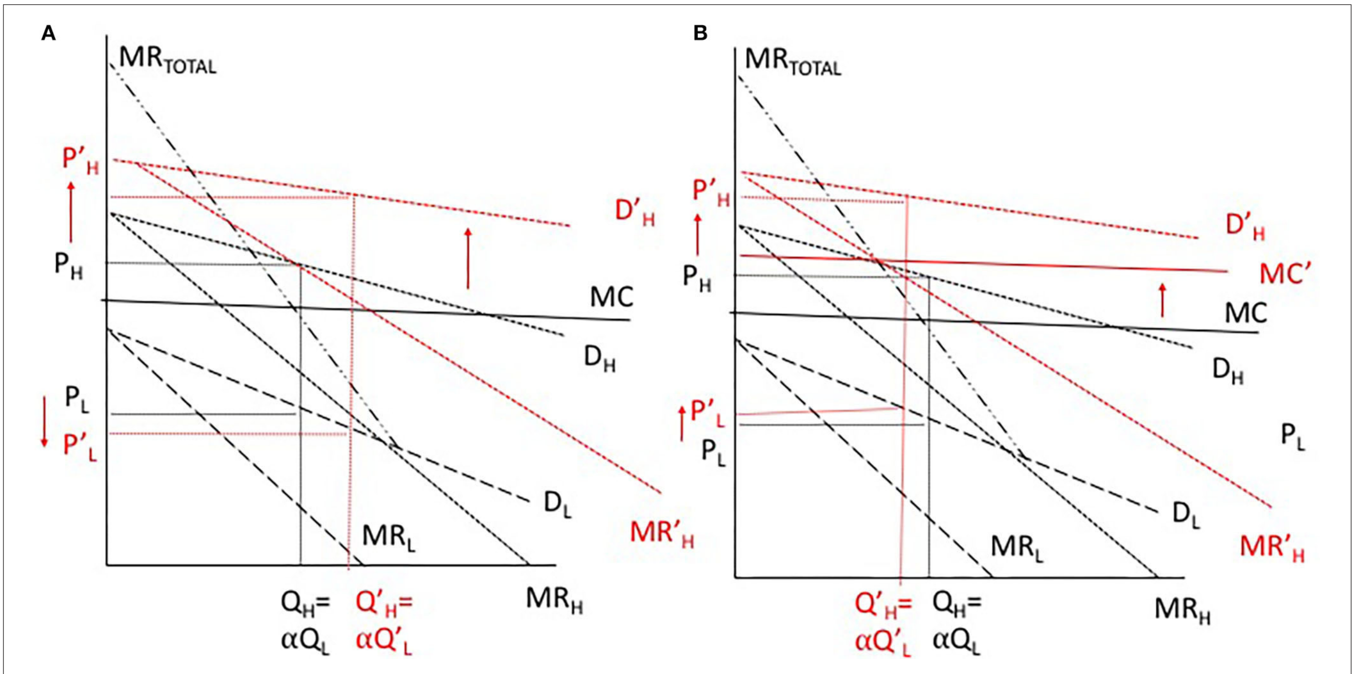

FIGURE 4 | Pricing of joint products under monopoly pricing under scenarios of increased demand **(A)** and increased demand and marginal cost **(B)**. Adapted from (18).

does not find an equilibrium in a neoclassical sense, but rather highlights the dynamic evolution of prices, production, and trade on a monthly basis.[3] As noted below, the model further considers the influence of macroeconomic variables, particularly exchange rate movements, on trade. **Supplementary Table 1** summarizes the data and assumptions used in the model and can be found in the **Supplementary Materials**. The equations for the model can also be found in the **Supplementary Materials**.

The SD model was used to run the following scenarios. Our first scenario explores the possibility of pursuing higher-value markets to improve pricing flexibility of different cuts to maximize carcass value. The other scenarios chosen highlight some of the key constraints in the beef value chain, that is, low productivity, relatively high marginal costs, and exchange rate volatility as noted in Ouedraogo (8) and Suleman (7).

1. A market segmentation strategy in Burkina Faso, whereby alternative high-value markets are found for higher quality cuts to allow greater pricing flexibility of offals into Ghana;
2. Improving animal productivity by increasing the weight of domestic animals slaughtered in Burkina Faso from 240 to 300 kg;
3. Improving meat processing efficiency through a reduction in the marginal costs of processing in Burkina Faso by 20%;
4. Combinations of the first three scenarios;
5. Scenarios looking at macroeconomic factors, by assuming no depreciation of the Ghanian Cedi against the CFA (but depreciating against the U.S. dollar) – this could be interpreted as both countries adopting the proposed Eco currency.
6. Considering the competitiveness of Burkinabe offals in Northern Ghana, where lower transportation costs would reduce the landed cost of Burkinabe exports and increase the costs of transport of third market offals from the coast to inland markets in Ghana.

Transport Costs and Margins

To complement the data generated by the SD model, we estimated transport costs between Burkina Faso and Ghana to assess whether prices for offals from Burkina Faso generated by the SD model would be competitive in Ghana with third-country imports after accounting for transportation costs. Teravaninthorn and Raballand (26) estimated transport costs from Ouagadougou to Tema at US$3.53 per km, or US$3,530 given the 1,000 km distance between the two cities. Assuming a 25-ton container of offals at 1,000 CFA[4]/kg (US$1.74/kg at the prevailing exchange rate in 2018), this implies a transportation cost of about 8% of the container value. However, the study by Teravaninthorn and Raballand (26) did not specify whether such costs were for refrigerated transport or not, which would be needed to facilitate such trade. Vilakazi (27) estimated refrigerated transport costs for selected routes in Southern Africa, which ranged from US$0.06/ton/km from Johannesburg to Cape

[3] In the absence of population or other growth, the model would (and does) converge to a steady state. However, system dynamics models model the price formation process somewhat differently than a neoclassical economic model as noted above.

[4] CFA stands for Communauté Financière Africaine (African Financial Community) and is the predominant currency used in Francophone West Africa. It is pegged to the Euro at 1 Euro = 655.957 CFA.

Town to US$0.13/ton/km from Johannesburg to Harare. Braun (28) notes similar costs in South Africa for container transport (US$0.05/ton/km) but small loads have much higher costs (a 5.5-ton van would cost US$0.23/ton/km). Taking the highest of these figures (US$0.13/ton/km) and applying the difference in transport costs between those found by Teravaninthorn and Raballand (26) in West and Southern Africa (52% higher costs in West Africa) yields transport costs of US$4,940 for a 25-ton container of offals, or about 11% of container value. From these ranges, we assume transport costs of 10% for our analysis.

Social Accounting Matrix Assessment

The other method used in our analysis was the use of a social accounting matrix (or SAM) to quantify prospective macroeconomic and employment effects associated with (a) an expansion of current types of live animal trade and (b) a shift toward meat exports in lieu of live animal exports. A SAM represents a ledger of economic activities within an economy, with such activities specified into accounts that represent aggregates of different sectors, factors of production (labor, capital), and households (29). A SAM is an accounting model whereby the rows of a SAM represent the income received by an account from other accounts, while columns represent expenditures on different accounts; by principles of double-entry accounting, total revenues must equal total expenditures.

SAMs can be transformed into a platform for scenario analysis through the computation of multipliers. A SAM multiplier denotes the economy-wide impact of a one-unit increase in exogenous government spending, investment, or export demand. These multipliers can be aggregated to quantify the total impacts on the value of production output, GDP, or household income. To quantify the impacts of a more specific shock, a matrix of multipliers can be derived. The matrix of multipliers is generated by first computing the SAM's A matrix, where the A matrix comprises the input-output coefficients of the SAM for its endogenous accounts (activities, commodities, factors, and households). Each element of the A matrix, a_{ij}, comes from dividing the corresponding *ij* element of the SAM by the column (*j*) sum. Then, the A matrix is subtracted from an $n X n$ identity matrix to generate a matrix (I-A), which is inverted to create a matrix of multipliers, or Leontief inverse (29). Changes to final output can be computed by multiplying the multiplier matrix by an $n X 1$ column matrix of final demand (government spending, investment, or export demand) and seeding that matrix with shocks to the appropriate row. To compute changes in export demand for live animals or meat, this entails inputting a value in the relevant commodity row and multiplying that matrix by the multiplier matrix.[5]

In addition, the SAM can be used to compute employment multipliers which show the number of jobs resulting from similar exogenous shocks (30). To do this, we used employment data for Burkina Faso reported by Zidouemba (31) that specified employment by sector aggregate (agriculture, industry, etc.). From the Burkina SAM, we calculated the total wage bill for these aggregated categories and estimated an average aggregate wage by dividing the total wage bill by the number of employees per aggregate category. We then applied the appropriate average wage to the disaggregated SAM accounts to estimate the number of jobs per SAM account. Following ILO (30), we then computed a matrix of employment-output ratios from the SAM accounts (using commodity rows and activity columns of the SAM), which are the number of workers needed to generate 1 million CFA of output. The matrix was multiplied by the relevant partition of the SAM multiplier matrix (commodity rows and activity columns) to generate an employment multiplier matrix, to which our scenarios were applied.

In our SAM analysis, we derived two export demand shocks. We first considered a doubling in the value of live animal exports based on the value found in the 2013 SAM. In the SAM, live cattle exports were estimated at 19.17 billion CFA in 2013, which assuming a value of a live animal of 300,000 CFA suggests live animal exports of nearly 64,000 animals. By contrast, official statistics from **Table 1** indicate trade volumes in 2013 were more than five times this figure. To obtain a more realistic indication of an increase in live cattle exports, we took the figure in the SAM and doubled it for exposition. Second, we compute a like shock for meat, where we took an equivalent value of live cattle exports converted to meat based on the yield of products derived from the carcass. We estimated that a 19.17 billion CFA increase in live cattle exports was analogous to 23.09 billion CFA in meat equivalent, based on the value of meat and offals. We used figures from Ouedraogo (8) for live cattle, carcass yield, and offals to estimate these conversion factors.

RESULTS

Baseline Competitiveness Assessment

Our results on baseline competitiveness can be found in **Tables 4**, **5**. Our focus is on offals, not cuts, given high demand for such products in Ghana. We estimated the ability of Burkinabe offals to be competitive in Ghana, based on current sales prices, transport prices, and an assessment of competitors. In **Table 4**, we first estimate the wholesale price of offals from non-Sahel sources based on the FOB prices reported in **Table 3** and transport costs, taxes, and margins obtained from Ouedraogo (8) and Suleman (7). Depending on the margin received by the trader, we estimate that average wholesale prices of offals range between US$1.81–1.86/kg (1,043–1,073 CFA/kg); we note this range hides considerable diversity in pricing of different types of offals but gives a plausible indication of the prices for such products.[6]

In **Table 5**, we then posit the export of Burkinabe offals to Ghana, based on current, ex-abattoir prices of offals (1,000 CFA/kg) and an estimate of transportation costs derived from data from Vilakazi (27), Braun (28), and Teravaninthorn and Raballand (26) as noted earlier. Based on these estimates, and informal fees reported in Suleman (7) and Ouedraogo (8), we estimate that the landed wholesale price of fresh Burkinabe offals would be around 1,111 CFA/kg, lower than the price of domestically-produced fresh offals in Ghana (1,416 CFA/kg) but

[5] More details can be found in Sadoulet and de Janvry (29).

[6] VAT of 18% was not applied in our scenarios as it applies equally to Burkinabe and non-Burkinabe sourced products.

TABLE 4 | Estimates of prices of imported offals in the domestic Ghanaian market.

Item	High trader margin (8%)	Low trade margin (5%)
FOB price imported offals	1.11	1.11
Freight costs (3,500 Euro for 40' container, 25 tons)	0.17	0.17
CIF unit value	1.28	1.28
Tariff (@35%)	0.45	0.45
Trader margin (@min 5%, max 8%)	0.14	0.09
Wholesale price (USD/kg)	**1.86**	**1.81**
Wholesale price (CFA/kg)	1,073	1,043

UN Comtrade for FOB prices (refer to ***Table 3****); informant interviews (July 2018) for freight costs and trade margins. Bold value is the sum of the figures above.*

TABLE 5 | Comparison of potential Burkinabe offal export prices and Ghanaian domestic prices.

Item	Price
Pricing of offals from Burkina Faso	
Price of offals, ex-abattoir Ouagadougou, CFA/kg	1,000
Transport costs (10%), CFA/kg	100
Informal charges (1%), CFA/kg	11
Landed price, CFA/kg	1,111
Comparative prices in Ghana	
Price paid by butchers in Ghana, CFA/kg equivalent	1,416

Price and informal charge information compiled from data from Suleman (7) and Ouedraogo (8). Transport costs derived from Vilakazi (24), Braun (25), and Teravaninthorn and Raballand [26]. Prices in Ghana are initially in Ghana Cedis and converted at an exchange rate of 1 Cedi = 117 CFA. See text for details.

higher than the world prices ranging from 1,043–1,073 CFA/kg reported in **Table 4**. Even if these Burkinabe prices could be lowered, a number of caveats need to be pointed out, however. First, the acceptability of chilled offals vs. fresh offals in the market is not clear—indications from Suleman (7) and Delavigne (32) are that there is a strong preference for fresh offals and that chilled/frozen products would sell at a discount. Second, the logistical viability of selling chilled offals needs to be explored more thoroughly—Meat and Livestock Australia[7] note that the shelf life for chilled offals is only about 7 days, and thus exports of chilled offals would require capable logistics that would add costs. Finally, if we consider the potential competitiveness in frozen offals (where such exports are likely more viable), our initial estimates do not consider the added costs of infrastructure (particularly freezing technology) that would be needed for such trade. Given the slight difference in current price gaps, the viability of such trade in frozen offals seems marginal at present, and sensitive to a variety of potential shocks (exchange rates, etc.) that we address in the scenario analysis.

Scenario Analysis of Alternative Marketing and Trade Protocols

In **Figure 5** through 7, we provide results from our scenario analysis with our SD model. We present results starting from year 3 (month 36) to highlight the steady-state of animal herd dynamics[8]. **Figure 5A** extrapolates the status-quo scenario given in **Tables 4**, **5** over the 10-year simulation period, taking into account the adjustment of live animal and meat markets. While **Figure 5A** shows large gaps in prices between domestically produced offals in Ghana and prospective fresh offals from Burkina Faso, the price of Burkinabe offals is consistently above the price of third-country imports. These gaps widen over time given the relative influences of exchange rate fluctuations, demand growth in both countries, and world price changes.

In **Figure 5B** through 7, we consider a number of alternative scenarios to explore whether various technical or marketing interventions may improve the status quo situation, with results illustrated against the baseline scenario of **Figure 5A**.

In the first scenario, we consider the development of high-value markets for high-quality cuts in Burkina Faso. This could be achieved either domestically and/or by sales to third markets. We consider an extreme scenario where Burkina Faso can achieve a price of 4,000 CFA/kg for its high-value cuts (compared to 2,000 CFA/kg in the baseline). **Figure 5B** reveals that this strategy slightly raises the domestic price in Ghana for offals, as greater demand for meat induced by market segmentation in Burkina Faso reduces the available supply of animals for trade. On the other hand, the price of Burkinabe offals is only slightly lower throughout the simulation period relative to the baseline, thus increasing the price gap between Burkinabe and Ghanaian sourced products. However, as the reduction in the Burkinabe price is modest, it fails to reach more competitive prices with third-country markets.

Improvements in animal productivity result in small reductions in the domestic price of offals in Ghana but have modest effects on the price of Burkinabe offals in the Ghanaian market (**Figure 5C**). Such a policy has benefits for domestic consumers in both countries for local products, but imported third-country products remain more affordable. Reducing the marginal costs of processing in Burkina Faso (**Figure 5D**) has slightly counter-intuitive effects. While it lowers the price of Burkinabe offals into Ghana, it very slightly raises the price of domestically produced offals through a similar mechanism as the market segmentation strategy. Namely, reducing marginal costs increases demand for animals in Burkina Faso for processing, lowering availability for trade, and raising the price of live animals. A combined strategy (**Figure 5E**) reduces prices in both

[7]https://www.mla.com.au/globalassets/mla-corporate/research-and-development/program-areas/food-safety/pdfs/shelf-life-of-australian-red-meat-2nd-edition.pdfcombinations of strategies.

[8]Typically, from a given set of herd demographic parameters, it takes two to three years in the model for herd growth patterns to reach a steady state, with production figures (and corresponding impacts on prices and trade) reflecting the noise of adjustment in those first few years. In order to focus on the steady state, we present results starting from year three.

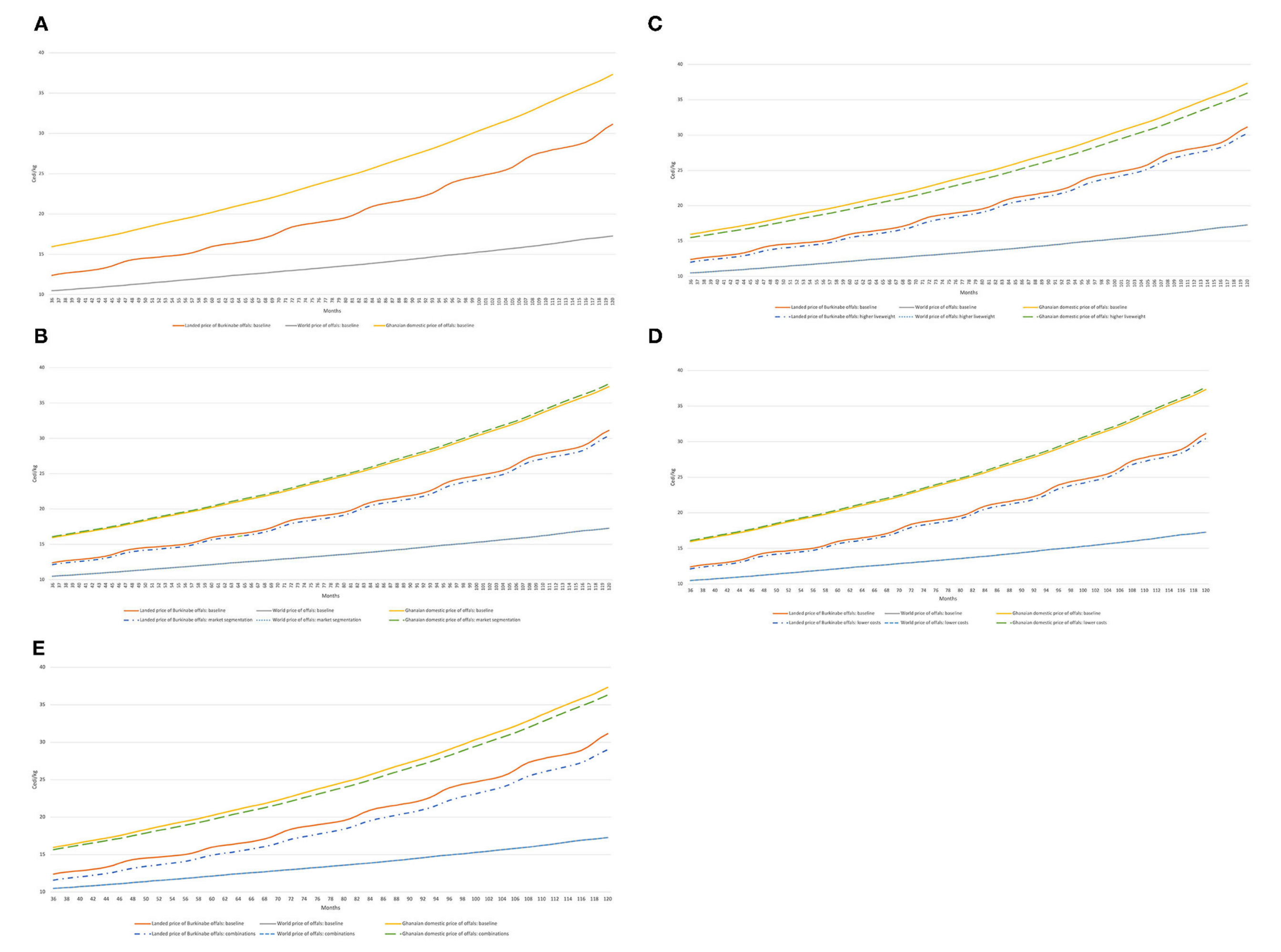

FIGURE 5 | Evolution of offal prices in Burkina Faso, Ghana, and world markets (Cedi/kg) under alternative strategies. **(A)** Baseline. **(B)** A price segmentation strategy. **(C)** Improved animal productivity. **(D)** A reduction in marginal costs in processing in Burkina Faso. **(E)** A combination of strategies **(B)**, **(C)**, and **(D)**. Model simulations.

Ghana and Burkina Faso and brings Burkinabe prices closer to third-country prices, but a significant gap still remains.

The macroeconomic scenarios in **Figure 6** produce perhaps the most interesting results. A stronger Cedi against the CFA brings Burkinabe prices on its own much closer to third-country prices in Cedi terms (**Figure 6A**). Combining this with the scenarios described above (**Figure 6B**) enhances Burkina Faso's competitiveness, though policies to make this actionable are largely out of the remit for agricultural ministries. Finally, while Burkinabe offals would be cheaper in Northern Ghana than on the coast, results from **Figure 7** highlight a similar, albeit smaller competitiveness gap with third country imports.

Macroeconomic Impacts of Alternative Trading Scenarios

Results from the SAM analysis can be found in **Table 6**. We remark that the CFA value of reported findings reflect conditions prevailing in 2013. However, as SAM multipliers are typically robust over several years, using the percentage change of different indicators provides a more interpretable metric that is invariant to the specific base year of the SAM, and will be the focus on the narrative below.

The SAM results indicate that higher export demand for meat generates more gross production, GDP, and household income than a similar shock in live animal export demand. However, the difference between the two scenarios is fairly modest. For instance, GDP rises by 0.09% more and household incomes by 0.06% under increased meat demand compared to increased cattle demand. On the other hand, the value of production output rises considerably more (by 0.3%) under a scenario of increase meat export demand, ostensibly given higher multipliers for meat as compared to live cattle. Employment effects are fairly modest in each case. Using 2013 figures, the number of jobs rise by 23,403 under increased live animal demand, and by 26,940 under increased meat demand, a difference of just 3,537 jobs.

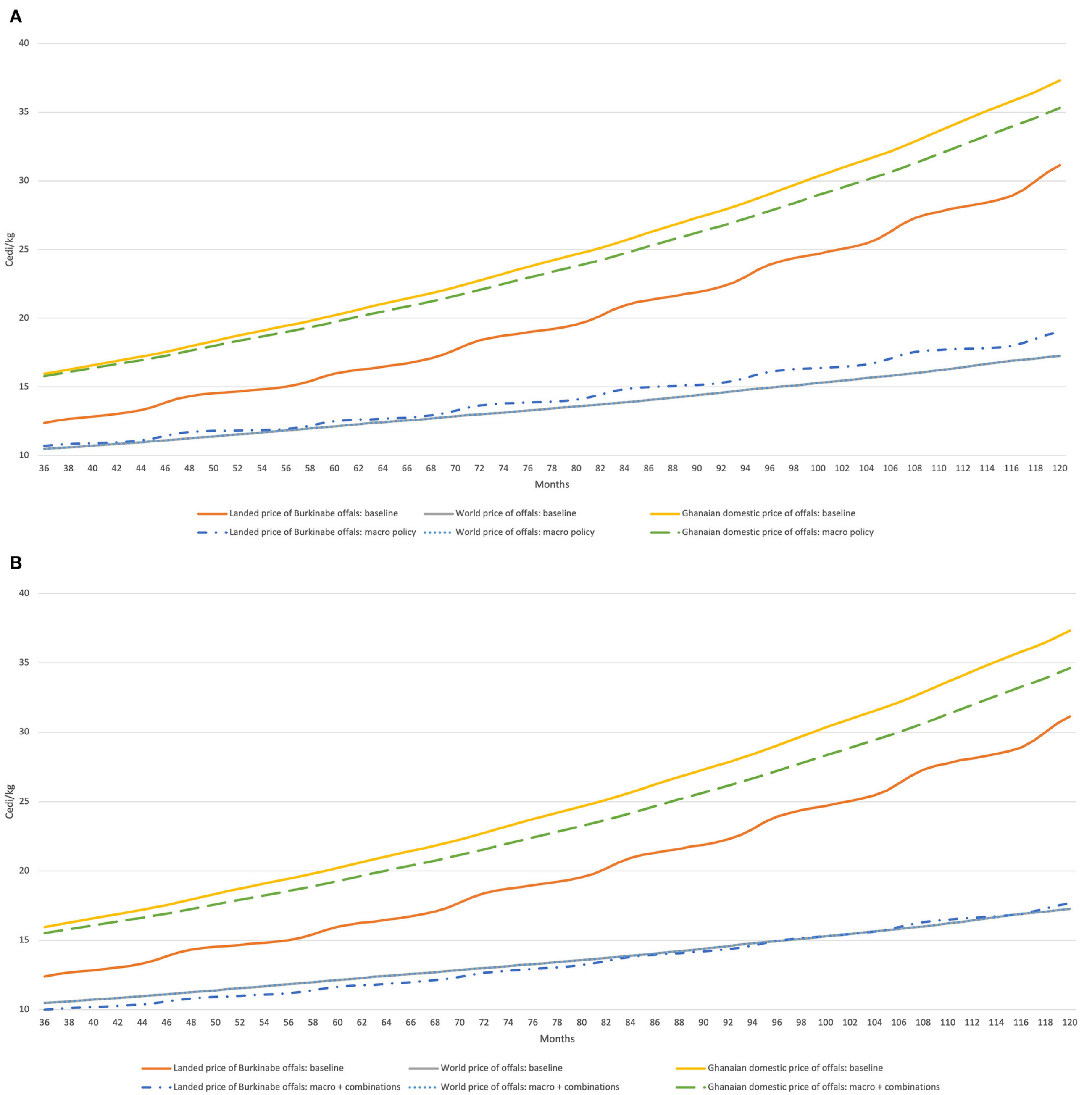

FIGURE 6 | Evolution of offal prices in Burkina Faso, Ghana, and world markets (Cedi/kg) under alternative macroeconomic regimes. **(A)** Baseline plus no depreciation of the Cedi vs. the CFA. **(B)** Macroeconomic changes from **(A)** + combinations of strategies (from **Figure 5E**). Model simulations.

DISCUSSION

From a meso and macroeconomic point of view, competitiveness refers to a broader concept. It is relative to the set of factors enabling a sector to generate growth, contribute to national wealth and improve the standard of living of its inhabitants. This is particularly relevant in the livestock sector in West Africa whose economic contribution, although often underestimated, remains very important. From a value chain perspective, live ruminant exports have shown their resistance to multiple barriers and an adaptability to multifaceted changes. However, very few quantitative studies of regional trade and its relative competitiveness exist for West Africa. This case study on the Burkina Faso-Ghana trade corridor addresses this gap and reveals a number of important findings.

In the context of the long-standing trade between Sahelian and the coastal countries of West Africa, our analysis highlights the persistent lack of competitiveness in prospectively traded

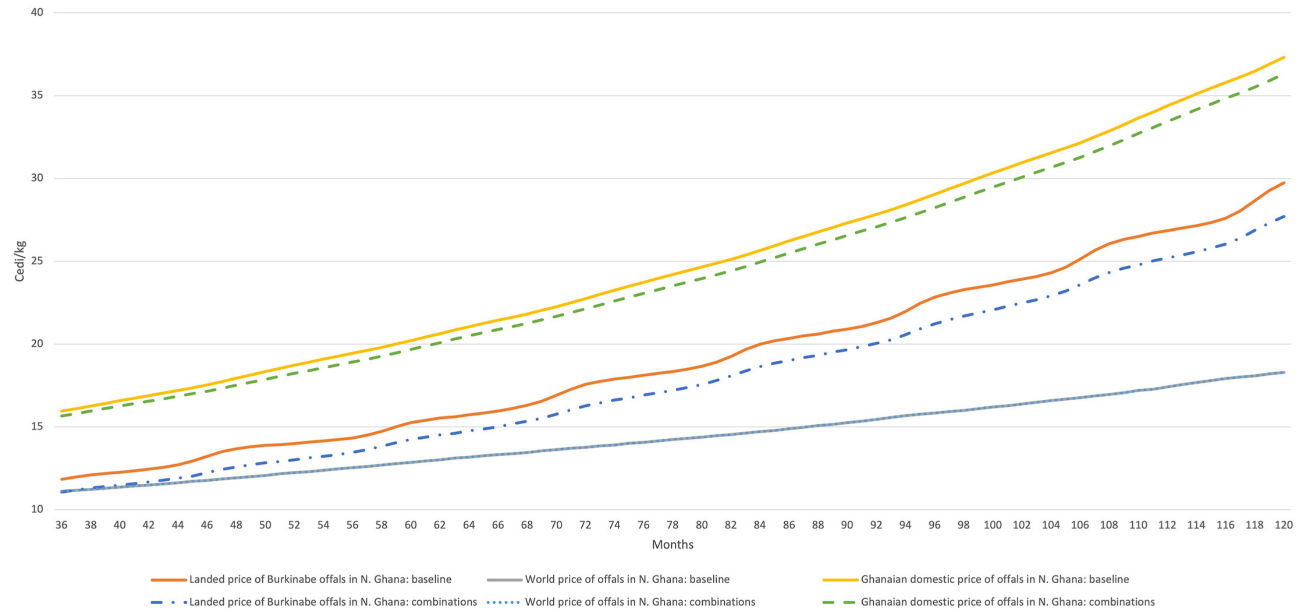

FIGURE 7 | Evolution of offal prices in Burkina Faso, Ghana, and world markets (Cedi/kg) under a combination of strategies—focus on Northern Ghana. Model simulations.

beef products (offals) vs. third markets. While there are clear price gaps between the prices of fresh/chilled Burkinabe offals and fresh Ghanaian offals that in the absence of external competition would warrant further promotion, third country imports remain cheaper in coastal markets. None of our proposed scenarios—improved market segmentation, enhanced animal productivity, or reduced processing costs—significantly address those gaps. Those policies are not without merit on their accord. For instance, greater market segmentation will give Burkina Faso more pricing flexibility for its beef in the future, while there are clear upstream benefits to producers and processors in better animal and herd productivity through improved feeding techniques; eradication and control of animal diseases and reduction of pre- and post-production losses. But these policies should be looked at more holistically from the standpoint of improving the livestock and meat sector more generally, and not as a "silver bullet" that yield immediate gains.

If we take the analysis a step further, price differentials may encourage both coastal and Sahelian countries to engage in a non-cooperative game of pursuing infrastructure development. The idea of building slaughterhouses in Sahelian countries is attractive for several reasons. In addition to capturing added value, it makes possible a means to reduce conflicts and potential losses linked to pastoral displacement, improve financial management ratios, create jobs (directly and indirectly in ancillary services), allow countries to converge toward reference health standards, and improve the capacities of actors in the sector. However, this change of paradigm should be carried out in a reasoned manner. Otherwise, their effectiveness and relevance could be severely hampered by insufficient and inadequate supporting infrastructure (poor roads and connectivity; trucks that do not meet standards for the proper conservation and transport of chilled and frozen meat) as well as by governance issues on in the value chain. With such a shift in paradigm, new governance issues emerge including road hassles; changes in sanitary standards for live animals; changes in pricing and marketing mechanisms; the potential transfer of jobs from coastal countries to Sahelian countries; and destruction of other service jobs along the live cattle marketing chain.

Our case study highlights the "curse" of borders in the context of the livestock trade across West Africa. The organization and spatial dimensions of this trade reflect a rational and intrinsic logic based on the resource base and demand amongst participating countries. Similar marketing patterns are found elsewhere amongst major beef suppliers globally. In Argentina, for example, the marketing of cattle has a distinct spatial dimension whereby animals are bred in the drier parts of the north of the country, fattened in the Pampas, and slaughtered in major cities (Buenos Aires, Rosario). The difference in the Argentine case is that the value added of production remains in one country and is not competed with our fought over as it is increasingly in the Sahel and West Africa. The development of innovative institutions fostered by greater regional integration and governance structures that share the benefits of this trade could be one way to better link and foster collaborative actions that sustainably build and grow this value chain.

Although our case study of the Burkina Faso—Ghana trade corridor provides very interesting findings, a broader study of trade dynamics across West Africa would be a useful area for future research. In particular, greater work on the dynamics of markets in and those that serve Nigeria would be critical given

TABLE 6 | Scenario analysis of live animal vs. meat exports of output, GDP, employment, and household income.

Indicator	Scenario 1: increased live animal export demand	Scenario 2: increased meat export demand
Change in gross production (million CFA)	43,818 (0.47%)	72,178 (0.77%)
Change in GDP (million CFA)	30,429 (0.57%)	34,845 (0.66%)
Change in employment (# new jobs)	22,938 (0.41%)	26,587 (0.47%)
Change in household income (million CFA)	23,403 (0.49%)	26,940 (0.56%)

Simulation analysis conducted with the 2013 Burkina Faso SAM (9).
Scenario 1 represents a doubling of the value of live animal exports relative to values reported in the SAM. Scenario 2 converts the shock in scenario 1 to meat equivalent value based on carcass yield and price differentials reported by Ouedraogo (8) and applies this to increased exports of meat (produits d'abattage in the SAM). Gross production, GDP, and household income are reported as percentage changes from gross value (million CFA), while employment is reported as the percentage change in the number of formal jobs. See the text for details.

its importance as the largest consumption market for the region. Linking such modeling platforms at pan-Sahel level to address substitution effects within and across markets and their dynamics would also be a valuable way forward.

CONCLUSIONS

In this paper, we developed a comprehensive approach to better understand the prospective gains of exporting beef from Burkina Faso to Ghana rather than live animals. Our analysis indicated that while Burkina Faso would be directly competitive in Ghana in meat (offals) given lower prices for offals produced in Burkina Faso, these prices remain higher than third country suppliers, as live animal prices and production costs are generally higher in West Africa. Market segmentation strategies, infrastructure development, and animal productivity all generate marginal improvements in competitiveness, but not enough to displace competitors. Live animal exports remain an important pathway for trade for Sahelian countries like Burkina Faso, and general investments in the sector can both enhance those exports and lead toward a path of greater regional integration to foster value-adding in the sector.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

KR and AW jointly developed the study design, collected data, and drafted the manuscript. KR constructed the system dynamics model used in the report and conducted the SD and SAM analyses. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Supply Chain and Delivery of Antimicrobial Drugs in Smallholder Livestock Production Systems in Uganda

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This study assessed the veterinary drug supply chain in Uganda, the constraints faced by the actors, and how the challenges influence the use of antimicrobial (AMs) by livestock farmers. We carried out stakeholder consultation workshops, key informant interviews and a knowledge, practices, and awareness survey with actors of the veterinary drug supply chain. We also profiled drugs stored in 23 urban and peri-urban drug shops in Lira and Mukono districts to record the commonly sold drugs. The veterinary drug supply chain is made of several actors including wholesalers, retailers, Animal Health Service Providers (AHSP) and farmers. Nearly ninety per cent of drug retailers and veterinary practitioners did not receive specialized training in veterinary medicine, and most of veterinary practitioners have been in the drug business market for more than 10 years. Antibiotics and anti-helminthics were the most stocked drugs by retailers, with antibiotics ranking highest in terms of contribution to annual financial profits, accounting for 33%. The choice of a drug by veterinary practitioners was mainly informed by past success with efficacy of the drug, and financial capacity of the client (the farmer) to meet the treatment cost. Many veterinary practitioners were not conversant with veterinary drug policies of the country, with Mukono having a higher number (72%) compared to Lira (37%). Veterinary practitioners from Lira district compared to Mukono and those mainly serving small scale farmers relative to large scale smallholders were more knowledgeable about antibiotics and AMR. Several supply chain constraints were identified as potential drivers of misuse of antibiotics that could contribute to AMR. These included low level of education of supply chain actors, particularly drug retailers, poor handling of drugs at purchase and administration practices, low enforcement of policies and regulations, and lack of awareness of stakeholders about policies that regulate drug use. Thus, future interventions to reduce misuse of AM drugs in livestock production systems in Uganda such as capacity building, should also target veterinary input suppliers, and deliberately involve a strong policy advocacy component.

Keywords: antibiotic, antimicrobial resistance, livestock, veterinary drug supply chain, Uganda

INTRODUCTION

While access to quality drugs by livestock producers remains a challenge, there is also misuse of drugs that are easily accessible. The voluntary and involuntary misuse of veterinary drugs such as antimicrobials (AM) in food-producing animals has the potential to generate residues in animal derived products (meat, milk, eggs and honey) and poses a health hazard to the consumer (1). For example, Dar et al. (2) reported that there is a high level of farmer self-prescription, with around a third of countries allowing over-the-counter sales of drugs. This situation is not only an indicator of poor-quality animal health services and animal husbandry practices but may also result in an increase in AMR risks in both animals and humans. While high income countries have improved structures to better monitor quality and quantity of veterinary drugs in the market, as well as testing AM residues in animal source foods, most low- and middle-income countries such as Uganda face challenges to put in place adequate systems to monitor veterinary drugs use in the livestock sector. Since the structural adjustment programs in the 1980s, in Uganda, like in many other sub-Saharian countries, the private sector has contributed immensely to the delivery of animal health services, and government's role has become largely regulatory (3). However, implementation of regulations and policies that govern the delivery of veterinary drugs is a challenge due to lack of resources and commitment of the government (4). Veterinary input suppliers such as drug wholesalers, retailers and veterinary practitioners are important actors in the drug supply chain, since they play an important role in ensuring quality of products to livestock farmers (5, 6). However, few studies have addressed veterinary drugs supply chain issues, especially in relation to AMR. The present study is a first step toward a comprehensive assessment of the use of AMs in smallholder livestock systems in Uganda. Its objectives are to understand the veterinary drug supply chain, constraints faced by actors, assess knowledge, practices, and awareness of veterinary drug suppliers on drug use and management practices, document policy gaps and how they influence the use of AMs. The study was implemented using three approaches: (1) qualitative assessment and description of the veterinary drug supply chains and its challenges; (2) profiling of veterinary drugs stocked by retailers and description of sales practices and (3) a KAP survey with veterinary practitioners about AMR and their perception of policies that govern the sale of veterinary drugs.

MATERIALS AND METHODS

Study Sites

The study was conducted in Kampala, Mukono, and Lira districts in Uganda. Kampala is the capital city of Uganda from where major drug wholesalers carry out their business. Mukono district is in central Uganda located 40 km from Kampala, with a population of 596,804 people, of which 59% are involved in agriculture (7). Because of the proximity to Kampala, livestock farmers are assumed to have better access to veterinary drugs and other animal health inputs. Lira District is in Northern Uganda, about 300 km from Kampala, had an estimated human population of 377, 800 in 2010. The economy of the district is mainly based on agriculture, with 81% of the population engaged in subsistence farming with cattle being the main source of wealth, and bulls and oxen being a major source of traction, particularly for plowing (8). Piggery has increasingly become an important enterprise with 40% of sub-counties having piggery as a priority enterprise (9). The two districts were purposively chosen for their contrasting geographic situations to enable comparison in relation to implications of the locations on potential quality of veterinary inputs and their access by farmers.

Data Collection

Qualitative Assessment of the Veterinary Drug Supply Chains

Consultation With Stakeholders of the Veterinary Drug Supply Chains

Two workshops were held with stakeholders of the veterinary drug supply chains in Mukono district (May 2016) and Kampala (December 2017). These two areas were targeted because of their high density of veterinary drugs shops. The workshops were organized and facilitated by the researchers. Workshop reports were developed at the end of each session. The discussions during the workshops covered challenges faced by actors, and recommendations to improve drug supply chains.

In Mukono, the workshop brought together private sector such as drug stockists, government [District Veterinary Officer (DVO) and drug inspector] and regulators [National Drug Authority (NDA)]. The stakeholders were also sensitized on the importance of application of best practices involving drug use, handling, and storage.

In Kampala, participants in the workshop included public and private veterinary services, drug retailers and the NDA and researchers (**Table 1**).

Key Informant Interviews With Large-Scale Drug Distributors (or Primary Wholesalers)

Independent in-depth face-to-face informal interviews were carried out with executives of the two major veterinary drug companies in the country at their headquarters in Kampala in November 2017. The discussions focused on description of the veterinary drug supply chains, as well as the regulatory framework for drugs distribution (**Table 1**).

Veterinary Drug Profiling and Description of Drug Sale Practices

Profiling of Veterinary Drugs Sold in the Market

The veterinary drug profiling survey was carried out by researchers in Lira and Mukono districts in August and September 2018, respectively. A list of registered veterinary drug retail shops was obtained from the DVO of the respective districts. Ten drug retailers in Lira and 13 in Mukono districts were included in the study. Most drug shops were in urban and peri-urban areas. The drug profiling exercise included recording of all drugs that were stocked in these shops at the time of the visits. The visit lasted an average of 4 h for each of the drug shops. Each drug was listed independently by trade name, and other data that were captured using photographic images included the active

TABLE 1 | Profile of participants to different activities.

Activity	Location	Target stakeholder	Target information	Number of participants
Qualitative assessment and description of the veterinary drug supply chains				
Stakeholder consultation workshop	Mukono	Private veterinarian (16), Drug stockist (7), Researchers (2), National Drug Authority (1), Senior Veterinary Inspector (1), District Veterinary Officer (1), District Animal Health Production Officer (1)	Document constraints in the drug supply chains at district level	29
	Kampala	District Veterinary Officer (1); Drug stockist (2); National Drug Authority officer (1); Researcher (1).	Document constraints in the drug supply chains at district level	5
Key Informant Interview	Kampala*	Distributor (primary wholesaler)	Understand the drug supply chain	2
Veterinary drug profiling and drug sale practices				
Drug profiling and informal interview with drugs retailers and field observations**	Lira	Drug retailers	Types of veterinary drugs sold and document sale practices	10
	Mukono	Drug retailers		13
Quantitative survey on knowledge and awareness about AMR with veterinary practitioners				
Survey on knowledge and awareness of AMR and related policies	Lira	Veterinary practitioners	knowledge, practices, and awareness on drug use an awareness about policies and regulations	32
	Mukono	Veterinary practitioners		68

*All large-scale veterinary drug distributors are in Kampala.
**Observations happened during the drug profiling in the same drug shops.

compound of the drug and indication for diseases which drugs identified could be used to treat. The qualification of the retailer and the number of years a specific drug has been on the market were recorded (**Table 1**).

Informal Interview With Drug Retailers and Field Observations

This activity was carried out purely *ad-hoc*. During the visits to the drug shops, interactions between the buyers and the drug stockists were observed and recorded. The researchers also engaged in informal discussions whenever necessary with the drug stockists to better understand their management practices and those of livestock keepers (**Table 1**).

Survey With Veterinary Practitioners on Knowledge, Practices, and Awareness About AMR and Perception of Related Policies

A list of all registered veterinary practitioners in urban and peri-urban areas was provided by the DVO of the respective districts. All registered veterinary practitioners were interviewed in both districts (Lira, 32 and Mukono, 68). Data on knowledge, practices of drug use and awareness of AMR were collected through a structured questionnaire. The questionnaire was digitalized through ODK (Open Data Kit) installed on tablets and uploaded to a server. The questionnaire was pre-tested by the researchers and refined before being administered by trained extension agents who operate in the study areas (**Table 1**).

Data Management and Analysis

Qualitative Analysis

The qualitative data was collected by researchers in notebooks during workshops, interviews, and field visits to drug shops, from which field reports were derived. The analysis of data involved extraction and linking information on identified themes including "stakeholder mapping, practices, policy challenges, recommendations", pre-defined key themes such as challenges faced by drug supply chain actors and practices in drug management. These reports also served as a basis to map the drug supply chain and document issues related to drug management.

Quantitative Analysis

The quantitative surveys consisted of the veterinary drug profiling with retailers and the survey on knowledge, practices, and awareness of veterinary practitioners about AMR and their related practices.

For the drug profiling, data obtained was recorded in MS excel to perform descriptive statistics. Generic drug names and active ingredients were used to classify the drugs into antibiotic, anthelminthic, arachnicide, vaccine, vitamin and iron supplement, antiprotozoal, disinfectant, anti-inflammatory and microbial supplement. Antibiotics were classified following OIE guidelines (11) into aminoglycosides, penicillins, quinolones, macrolides, polypeptides, sulphonamides, and tetracyclines.

For the knowledge, practice and awareness survey with veterinary practitioners, data was exported from the ODK server to STATA 15 (StataCorp) for further analysis. Descriptive statistics (frequencies and proportions) were carried out and whenever relevant, between districts comparisons were done

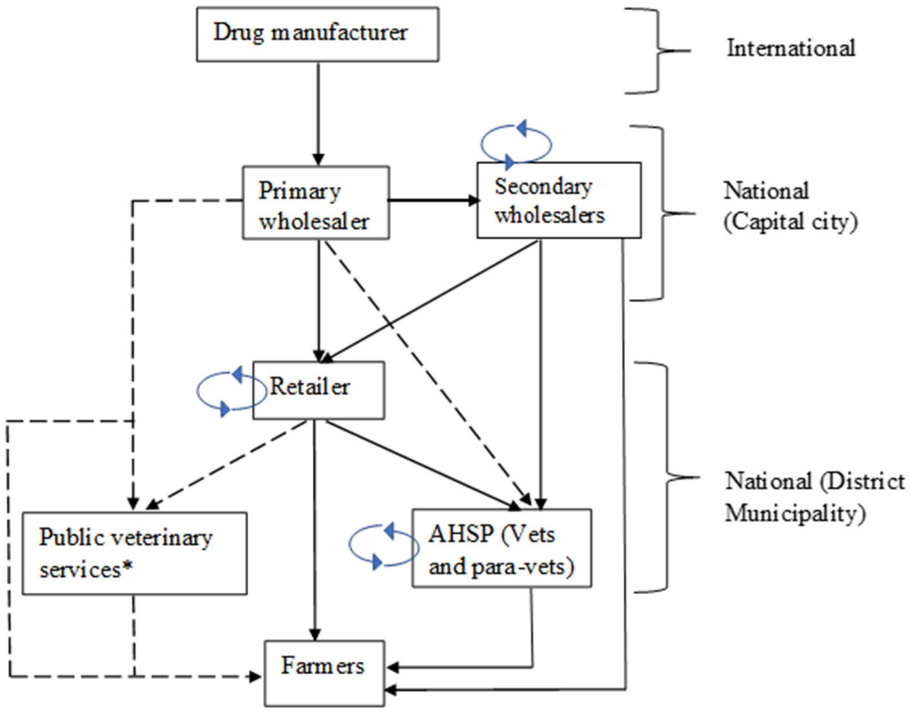

FIGURE 1 | Veterinary drug and vaccine supply chains in Uganda. The flux distribution was determined based on perception of stakeholders (Full line = high flux distribution channel; Dotted line = low flux distribution channel); *Public veterinary services procure mainly vaccines for endemic diseases and acaricides; Continuous loop indicated the back-and-forth sales among same stakeholders. The determination of the flux was based on the knowledge and perception of stakeholders.

using chi-square test. To analyse factors associated with appropriate knowledge of AMR by veterinary practitioners, a univariable analyse and a backwards stepwise selection Generalized Linear Models (GLM) was used. Each knowledge related question (**Appendix 1**) was independently analyzed by assigning a score to responses, either one (correct or appropriate response) or zero (incorrect or non-appropriate response). The scoring was done by the first author who is a veterinarian. To analyse how veterinary practitioners performed in the knowledge of AMR, the sum of each participant's answers was calculated. Those whose answered 70% or more correct were deemed to have good knowledge of antibiotics and AMR. Covariates with a $p < 0.05$ were included in the final multivariable analysis using GLM with a Poisson log linear link function, which was run in Stata package (StataCorp) version 14 to test the effect of different factors on the outcomes of interest (knowledge of AMR). A two-sided $p < 0.05$ was considered statistically significant.

RESULTS

Qualitative Assessment and Description of the Veterinary Drug Supply Chain in Uganda

Map of the Veterinary Drug Supply Chain

The supply of veterinary drugs in Uganda is made up of several actors who play distinct but complementary roles and who are mainly from the private sector. Drug manufacturers are the first level of actors (**Figure 1**). They are mostly based abroad and include international reputed pharmaceutical companies which have established a market in Africa. The primary wholesalers (or drug importers/distributors) are in the country and they hold large-scale business dealing directly with manufacturers. They supply drugs to secondary wholesalers and retailers, and to some extent to AHSPs and to the government. The secondary wholesalers hold medium scale businesses and mainly redistribute drugs to retailers (also called drug stockists) and to AHSPs such as veterinarians and para-veterinarians, who supply to farmers some of whom practice self-medication. Primary and secondary wholesalers have their main branches located in the capital city in Kampala. Drug retailers are located in the regions (or districts), and around municipalities from where they have access to infrastructures such as electricity. They mainly supply drugs to AHSPs and to livestock farmers. Drug retailers consider farmers as their first-choice customers because they pay higher prices as compared to AHSPs, who tend to bargain for lower prices as they have better market information of the products from wholesalers. Secondary wholesalers and retailers stock drugs based on demand forecasts, price, and profit margin. The transactions costs and their poor bargaining power may result in weak incentives for them to stock a wide variety of products or brands, leading to frequent shortage of products in the market. The government procures veterinary products for public use, especially livestock vaccines and acaricides, mainly from primary wholesalers.

The secondary wholesalers and retailers could buy drugs among themselves to accommodate market demand. This situation happens when a drug is scarce in some areas and is on excess in another area. The markets are constantly fluctuating, and products change hands many times. The determination of product prices at the supplier and the retailer nodes depends on the transaction costs incurred, mainly transport and storage. The distributors normally add a 15% charge for transport from the manufacturer to the primary wholesaler and a 30% mark-up (for distributor profit). The drug retailer stationed in the district adds a 30% for profit margin. At the farmer node, the cost of the drug is included in the service package of the AHSP.

The role of government in regard to regulation of veterinary drugs is divested to the NDA within the Ministry of Health. The NDA mandate includes supervision and control of importation, exportation of pharmaceuticals, promotion, and control of local drug production, as well as encouraging research and development of herbal medicines. Wholesalers and retailers hold a practice license provided by the NDA, which conducts routine monthly visits to drug dealers' premises to ensure compliance with regulations. The role of the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) is to provide extension and sensitization and capacity building of actors in the supply chain.

Challenges Reported by Drug Supply Chains Actors

The supply chain actors reported several constraints they face in the drug business. For example, repackaging of product in smaller units happens at different nodes of the supply chain. This practice can lead to product deterioration following exposure to abnormal temperature and sun light. There is weak enforcement of regulations such as quality control assurance which may accelerate proliferation of falsified or substandard products into the market. Actors reported that wholesalers do not have the same standard operating procedures for marketing drugs, as they all manage the product using own standards, which complicates quality control, thus absence of accountability if something goes wrong in the field including treatment failure or drug expiry. There is continuous questioning of farmers about the quality of drugs they receive since there are reported cases of poor effectiveness of some drugs after use. Regarding this, there is a blame game going on between retailers and farmers who accuse each other of being responsible for poor-quality drugs following poor storage and handling by retailers or inappropriate use by farmers.

Constraints reported by drug retailers include high transactions costs leading to high cost of the drugs, and consequently low profit margins particularly for small businesses that do not have sufficient financial capital. Uncontrolled transactions result in unethical competition, sidelining the small business owners, who then escape quality control.

Furthermore, farmers' fixed mindset does not enable smooth transition to accommodate new drugs in the market and is a barrier to drug uptake. For instance, farmers usually stick to known brands and are not flexible to change even though the active ingredient are the same. This situation prevents new drugs from penetrating the market, resulting in a limited range of options to farmers. Limited financial and human resources by authorities in charge of regulation of the drug supply chain were reported as a major challenge. According to stakeholders, inappropriate implementation of policies has led to lack of incentive of actors to comply to regulation. For example, lack of supportive measures such as compensation after drug confiscation by NDA makes some drug users not to report cases of drug expiry. Therefore, there has been an influx of substandard quality drugs in the market. The poor-quality drug or "fake drug" phenomenon was commonly pointed out by all actors as being a major issue. This is when a drug comes from a suspicious origin (e.g., unknown dealer to the community), or when farmers are deceived by health workers of treating non-curable diseases such as African swine fever. According to stakeholders, self-medication has gained ground, following poor access to quality drugs by farmers. It is therefore difficult to situate the responsibility of poor quality or "fake drug" when there is no traceability of products.

The actors recognize that there are gaps in the existing policy governing delivery of veterinary drugs, hence such a policy ought to be revised. A major gap identified is the poor collaboration between government bodies who play important roles in the delivery of drugs, and the laborious protocols and procedures for registering new drugs, leading to stakeholders taking "shortcuts" to release the product in the market. The actors also stressed the need to set-up regulatory authorities/bodies to track unqualified personnel. Major challenges reported by regulators include lack of personnel at district level; and lack of laboratory capacity for quality control especially for identifying fake drugs. They also mentioned that products licensed by NDA are of good quality and are efficient however drug stockists reduce the efficiency of the drugs through their practice. Poor practices of drug stockists include reconstitution of vaccines for retail sale or dividing the vaccine capsules; sale of expired drugs to farmers by changing labels to extend the shelf life of drugs or altering the expiry dates and also repackaging drugs. Therefore, drug shops are limited on the amount of stock at a given time as well as bulk packs. They further stated that the problem was not the drugs but the government policy of liberalization where everyone can run a drug shop for the money and not as a form of service.

Veterinary Drug Profiling and Drug Sale Practices

Sociodemographic Characteristics of Drug Retailers

Most drug retailers interviewed in Mukono and Lira were male, holding either a diploma or a lower academic qualification (**Table 2**).

Category of Antibiotics Stocked by Retailers

In total 1,172 drug brand names were recorded from the 23 drugs retail shops in districts of Lira, (29%) and Mukono (71%). Antibiotics (33%) and anthelminthics (26%) were the most stocked drugs by retailers in Lira district, while antibiotics (28%) and vitamins/minerals (25%) represented the most stocked drugs by retailers in Mukono district (**Figure 2**).

TABLE 2 | Demographic characteristics study participants (drug retailers) by district.

Variable	Category	Lira (*n* = 10)	Mukono (*n* = 13)
Gender of respondent	Male	8 (80%)	7 (54%)
	Female	2 (20%)	6 (46%)
Academic qualification	Bachelor of Science veterinary medicine	1 (10%)	1 (8%)
	Diploma in animal production*	4 (40%)	9 (69%)
	Certificate in animal production*	3 (30%)	2 (15%)
	Primary education	1 (10%)	0 (0%)
	Unknown	1 (10%)	1 (8%)

**Diploma and certificate programs help prepare students for higher education and advance their careers. They are usually short in length since they are intended to cover specific areas.*

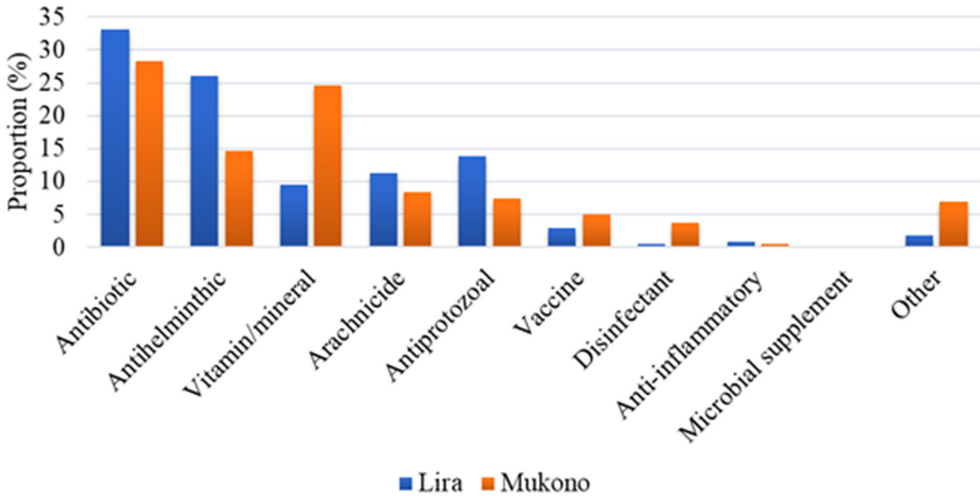

FIGURE 2 | Drugs and supplies/biologicals stocked in shops in Lira and Mukono districts. Other Category Includes Growth Promoters, Feed Additives, Detergents, Sedatives.

The most common classes of antibiotics recorded in both districts were tetracyclines (53%) and sulphonamides (18%), followed by macrolides (9%) and quinolones (7%). Polypeptides and aminoglycosides were the least frequently recorded group of antibiotics and were only found in Mukono. Within the class of tetracyclines, oxytetracycline was the most frequently encountered antibiotic compound; while sulfadimidine was the most frequently encountered antibiotic compound within the class of sulphonamides. All antibiotic compounds, except tylosin, were reported to have been in the market for at least 15 years, with oxytetracycline and procaine penicillin being the oldest with 30 years. Tylosin was reported to be the newest antibiotic substance on the market, available since about 8 years (**Table 3**).

According to the drug producer recommendations, the main routes of administration of antibiotics to livestock as recorded from the package were oral (51%), followed by intramuscular injection (15%) and topical application (13%). Other administration routes include sub-cutaneous, intra-uterine, intramammary, eye drop and intravenous.

Practices of Drug Retailers and Factors Influencing Drug Choice by Buyers

From the retailer's point of view, there is no restriction to whom they sell drugs to, and most of the time, buyers (mostly farmers and veterinary practitioners) ask for a drug they want by its trade name. This is influenced by their experience with these drugs or the duration of use of the drugs (usually those that have been on the market for long). Farmers mostly stick to the drugs they know and have been using in the past; they are reluctant to change to drugs that are new in the market. The cost of the drug was also mentioned as a factor that influences choice of the buyer, as some buyers weigh prices of different drugs and opt for the cheapest option. Location (drug shop close to client) was an important factor, and we observed that the urban shops received the most clients. Perceived effectiveness of the drug experienced by the buyer was another factor affecting drug purchase. It was reported that farmers communicate drug success or failure and recommend drugs that work to each other. When a buyer comes without prior knowledge, recommendations are made by the retailer based on the buyer's description of the clinical signs of the disease. From a AHSP perspective, the choice

TABLE 3 | Classes of antibiotics stocked in retail shops in Lira and Mukono districts.

Antibiotic class	Lira, $n = 114$	Mukono, $n = 234$	Total, $n = 348$	Antibiotic compound per antibiotic class
Tetracycline	67 (59%)	118 (50%)	185 (53%)	Oxytetracycline, 93% Oxytetracycline cocktail**, 6% Doxycycline, 1%
Sulphonamide	18 (16%)	44 (19%)	62 (18%)	Sulfadimidine, 32% Trimethoprim + Sulfamethazine, 29% Trimethoprim + Sulfadiazine, 27% Sulfamonomethoxine, 7% Sulphadimidine cocktail*, 5%
Macrolide	7 (6%)	23 (10%)	30 (9%)	Tylosin, 80% Erythromycin 20%
Quinolone	3 (3%)	20 (9%)	23 (7%)	Enrofloxacin, 87% Flumequin, 13%
Penicillin + Aminoglycoside	10 (9%)	9 (4%)	19 (5%)	Procaine penicilin + Dihydrostreptomycin, 83% Procaine penicilin + Neomycin + Streptomycin, 17%
Penicillin	6 (5%)	9 (4%)	15 (4%)	Cloxacillin benzathine, 92% Amoxicillin, 8%
Aminoglycoside	3 (3%)	9 (4%)	12 (3%)	Gentamicin, 75% Neomycin, 25%
Polypeptide	0 (0%)	2 (1%)	2 (1%)	Colistin, 100%

*Sulphadimidine + diaveridine, excipient, vit K.
**Oxytetracyclin + hydrochloride, neomycin sulfate, Vits A, D3, E B1,2, 6,12 K3, C, and Oxytetracyclin + nicotinamide, folic acid, methionine, lysine or Vits A, D3, E, K3, B2, B 12.*

of a drug takes into account the administration mode of the drug (easier to administer, not requiring lot of restraining as in the case of injectables), the preference of the farmer (single dose not requiring follow-up), the cost of the drug (affordable for the farmer). Given that most of the times there is no laboratory diagnostics carried out prior to treatment, ASHPs prefer broad spectrum anthelminthics such as ivermectin (targets internal and external parasites), or antibiotics such as oxytetracycline. Aliquoting drugs into small doses is common for buyers who cannot afford to buy the whole pack. This is carried out using syringes, empty drug containers, including empty vials dedicated for human drugs which are used to aliquot mostly injectable drugs.

Drug retailers noted that there is continuous advice to buyers about usage of drugs (dosage or usage frequency and duration of usage), especially for arachnicides and poultry drugs that require mixing or dilution before use. Most drug shops had a certificate of operation on display with the respective qualifications mentioned. However, the person whose qualification is displayed was most of the times not the person interviewed, nor the one doing the sales. We also noticed that drug shops are sometimes run as family business and a family member with no qualifications in animal health or animal production is involved in the sale of drugs. This helps cut expenses and probably tackles unemployment given the high unemployment rates in the area. Another scenario is that a person without specific veterinary sciences training is sometimes hired. It is also common for agricultural shops to get involved in the sale of veterinary drugs, although they are not licensed by the NDA. They sell "fast moving" drugs like oxytetracyclines, acaricides and wound sprays. It is however unlikely that someone would see these drugs as they are kept away from display and only brought out when a trustworthy client asks for them.

Survey With Veterinary Practitioners on Knowledge, Practices, and Awareness About AMR and Perception of Related Policies

Demographics and Services Delivered by Veterinary Practitioners Use

Majority of veterinary practitioners who took part in the survey were male mainly offering disease treatment services only. Most of them hold a diploma and have been practicing for at least 5 years (**Table 4**).

Antibiotics were mentioned to be the most profitable drug category for veterinary practitioners (Lira, 81% and Mukono, 59%). In both districts, practitioners dealt mostly with cattle and pigs. Practitioners who dealt with poultry were only registered in Mukono district. Most veterinary practitioners provided drugs to small scale farmers (Lira, 84%; Mukono, 73%) (**Table 5**).

Most veterinary practitioners reported administering drugs to animals or selling drugs to farmers without prescription (Lira, 37%; Mukono, 40%). They mostly decided on drugs based on symptoms as described by the farmer and verified by themselves (Lira, 75%; Mukono, 78%), or based on their own judgement following a farmer's explanation without seeing the animal (Lira, 25%; Mukono, 21%). Dosage was generally determined following instructions on the drug packaging, while weight of the animal was estimated by the farmer or the practitioner. According to practitioners, most farmers in Lira (87%) administered the drugs to animals by themselves. Drugs were mostly sold as single tablets

TABLE 4 | Demographic characteristics of veterinary practitioners.

Variable	Category	Lira (*n* = 32)	Mukono (*n* = 68)
q8-Gender of respondent	Male	29 (91%)	59 (87%)
	Female	3 (9%)	9 (13%)
q10-Nature of the business	Practicing treatment only	29 (91%)	49 (72%)
	Practicing treatment and drug retail shop	3 (10%)	19 (28%)
q11-Years in business	0–1 year	1 (3%)	5 (7%)
	2–4 years	9 (28%)	12 (18)
	5–10 years	14 (44%)	24 (35%)
	More than 10 years	8 (25%)	27 (40%)
q12-Academic qualification	Bachelor of Veterinary Medicine	1 (3%)	4 (8%)
	Bachelor of Science	0 (0%)	6 (6%)
	Diploma	21 (66%)	35 (51%)
	Certificate	5 (16%)	20 (29%)
	High school	1 (3%)	2 (3%)
	Primary school	4 (12%)	1 (2%)

TABLE 5 | Characteristics of business delivered to farmers by veterinary practitioners.

Variable	Category	Lira (*n* = 32)	Mukono (*n* = 68)
q17-Drug category important for the business	Antibiotics	26 (81%)	40 (59%)
	Antihelmintics	5 (16%)	18 (26%)
	Arachnicides	0 (0%)	3 (4%)
	Vaccines	1 (3%)	7 (10%)
	Vitamins	0 (0%)	0 (0%)
q13-Livestock dealt with most	Cattle	27 (84%)	34 (50%)
	Pigs	5 (16%)	20 (29%)
	Poultry	0 (0%)	13 (19%)
	Sheep/goats	0 (0%)	1 (1%)
q16-Customer to veterinary practitioners	Small scale farmer	26 (84%)	49 (73%)
	Large scale (commercial) farmers	5 (16%)	18 (27%)

by 25% of practitioners in Mukono, while 65% of practitioners said they provide enough drugs for the whole course of treatment with follow-up visits. There were complaints from several clients (farmers) about treatment failure (Lira, 44%; Mukono, 74%). Arachnicides/acaricides were reported to be the drug that failed most, followed by antibiotics and antihelminthics (**Table 6**).

Awareness and Knowledge of Veterinary Practitioners About AMR

Most veterinary practitioners had heard about AMR (Lira, 75%; Mukono, 79%) mainly through one-to-one communication among practitioners (50% and 35%, respectively, in Lira and Mukono). Other important awareness channels include during training sessions organized by government, by development organizations, broadcasting (radio and television), newspapers, and internet. The role of antibiotics was moderately understood, with majority of practitioners correctly indicating that antibiotics are effective in managing bacterial infections (Lira, 72%; Mukono, 75%). Knowledge about antibiotic residues in animal source foods such as meat and eggs and knowledge about withdrawal periods and processes of acquiring antibiotics residues through food products was very high. However, the ways humans can acquire resistance to antibiotics was not well-understood (**Table 7**).

Factors That Influence Knowledge of Veterinary Practitioners About Antibiotics and AMR

Awareness of veterinary practitioners about AMR, district of origin (Lira) and category of clients (small scale farms) had a positive effect on knowledge of veterinary practitioner about AMR (**Table 8**).

Perception of Veterinary Practitioners About Critical Actions to Mitigate AMR

Many veterinary practitioners were not conversant about veterinary drug policies of the country, with Mukono having a higher number (72%) compared to Lira (37%). However, the most urgent capacity needs according to practitioners in Lira were a better understanding of the policies about the use of veterinary drugs in the country and a better knowledge on how to use AMs in livestock. While in Mukono, the most urgent capacity needs were the understanding of the mechanism of AMR and a

TABLE 6 | Practices of veterinary practitioners in drug use.

Variable	Category	Lira (*n* = 32)	Mukono (*n* = 68)
q21-Sale of drugs to farmers	On prescription only (from another veterinary practitioner)	20 (63%)	41 (60%)
	Both with and without prescription	12 (37%)	27 (40%)
	Without prescription	0 (0)	0 (0%)
q24-Basis for deciding to administer or sell antibiotic to farmers	Symptoms as explained by the farmer and verified by veterinary practitioner	24 (75%)	53 (78)
	Laboratory test results provided by farmer or done by veterinary practitioner	0 (0%)	1 (1%)
	Own judgement following farmers' explanation (without seeing the animal)	8 (25%)	14 (21%)
q25-Estimation of dosage	As indicated on the drug packaging	13 (41%)	21 (31%)
	Own judgement based on experience of success	4 (12%)	26 (38%)
	Estimated weight of the animal by farmer or practitioner	15 (47%)	20 (29%)
	Other	0 (0%)	1 (1%)
q27-Way of administering the drug to animals	Single dose/one-time measurement depending on the farmers' capacity	2 (6%)	17 (25%)
	Whole package for whole course of treatment	2 (6%)	44 (65%)
	As indicated on drug packaging	0 (0%)	1 (1%)
	I don't administer*	28 (87%)	6 (9%)
q28-Drug failure reported by customers (farmers)	Yes	14 (44%)	50 (74%)
	No	18 (56%)	18 (26%)
q30-mnagement of expired drugs	Discard	29 (91%)	56 (84%)
	Never experienced	2 (6%)	2 (4%)
	Return to National Dru Authority	0 (0%)	1 (1%)
	Return to the wholesaler	1 (3%)	7 (10%)
	Sell to clients at cheaper price	0 (90%)	1 (1%)

**These categories of animal health practitioners sell the drug to farmers who administer by themselves.*

better knowledge on how to use AMs in livestock. Perception of veterinary practitioners about critical actions for the sustainable control of AMR include raising awareness of farmers about the impact of misuse of antibiotics; re-enforcement of disease control measures in livestock and stronger and directed policies on AM use (**Table 9**).

DISCUSSION

The veterinary drug business in Uganda is largely driven by private sector and is characterized by a diversity of actors who play distinct but complementary roles. The drug business is operated by personnel with sometimes limited training in drug management, which is in line with findings of Ilukor et al. (3) and Byarugaba (4) who reported that the animal health sector in Uganda has a high percentage of non-trained service providers. In most veterinary drug sale points, drugs can be accessed by anyone (veterinary practitioners or not), regardless of what drug is needed. This situation reflects the poor regulation of the veterinary drug market. Lack of traceability of drugs was widely pointed out by stakeholders as a major challenge leading to proliferation of "fake drugs" in the market. According to Granados-Chinchilla and Rodríguez (12), the Sub-Saharan African market is highly affected by counterfeit veterinary drugs. Though these counterfeit and non-compliance of drugs can induce adverse effects during their utilization, there is no monitoring system of veterinary medicines (13).

We found that all antibiotics (except tylosin) stored in drug shops have been on the market for at least 15 years, suggesting constant and wide use of these drugs in livestock. This situation also points to the limited diversity in the antibiotic classes marketed, with oxytetracycline and sulfadimidine being the common antibiotics accessed by farmers for many years. A study in Ghana, reported the same antibiotics to be commonly used in livestock in many smallholder livestock (14). Tetracyclines are a family of compounds frequently employed due to their broad spectrum of activity as well as their low cost, compared with other antibiotics. Currently, there are over 20 tetracyclines available; however, tetracycline, chlortetracycline, oxytetracycline, and doxycycline are the most common ones in veterinary medicine (15). In addition to therapeutic purposes, in many other countries, tetracyclines are often incorporated into livestock feed at subtherapeutic doses as growth promoters for swine and poultry and in aquaculture (12).

The lack of diversity in the use of drugs reflects the low level of sophistication of the drug market in Uganda, which is likely linked to the limited disease diagnostic capacities that prevail, hence restricting the choice of drugs, therefore leading to the constant use of broad-spectrum antibiotics more frequently. However, this lack of diversity in the use of drugs could also be a good thing as it reduces the risk of multidrug resistance to several classes of antimicrobials; considering the fact that that excessive use of antibiotics in humans leads to emergence of resistant organisms (16). The criteria for choosing a drug by veterinary practitioners which were mainly based on their experience with the drug was rather subjective; hence the change of giving a wrong treatment to animal is high. This is exacerbated by the fact that in most African countries

TABLE 7 | Knowledge of veterinary practitioners about roles of antibiotics and antibiotic resistance.

Variable	Category	Lira, *n* = 32	Mukono, *n* = 68	*P*-value
Awareness about antibiotic resistance				
q31-Heard about antibiotic resistance phenomenon	Yes	24 (75%)	54 (79%)	0.619
	No	8 (25%)	14 (21%)	
q32-antibiotic resistance awareness channel	Learned about AMR from my background training	8 (34%)	22 (41%)	0.615
	Heard from radio	2 (8%)	2 (4%)	
	Learnt from a colleague	12 (50%)	19 (35%)	
	Learnt from a short training/workshop	2 (8%)	9 (16%)	
	Red from newspaper	0 (0%)	1 (2%)	
	Other	0 (0%)	1 (2%)	
Drivers of antibiotic resistance				
q37-Antibiotic resistance is caused by using antibiotics when not indicated	Agree	19 (59%)	49 (72%)	0.205
	Disagree	13 (41%)	19 (28%)	
Roles of antibiotics				
q38-Antibiotics are effective in managing bacterial infections	Agree	23 (72%)	51 (75%)	0.740
	Disagree	9 (28%)	17 (25%)	
q39-Antibiotics are effective in managing viral infections	Agree	4 (12%)	30 (44%)	0.002**
	Disagree	28 (88%)	38 (56%)	
q40-Antibiotics are effective in managing protozoal infections	Agree	27 (84%)	49 (72%)	0.179
	Disagree	5 (16%)	19 (28%)	
q41-Antibiotics are effective in managing parasitic infections	Agree	6 (19%)	5 (7%)	0.089
	Disagree	26 (81%)	63 (93%)	
q45-Antibiotics are effective in managing pain and inflammation	Agree	27 (84%)	53 (78%)	0.453
	Disagree	5 (16%)	15 (22%)	
q43-Antibiotics are effective in boosting animal growth	Agree	25 (78%)	19 (28%)	0.000**
	Disagree	7 (22%)	49 (72%)	
Antibiotic residues				
q44-Residues of antibiotics can be found in meat	Agree	31 (97%)	61 (88%)	0.218
	Disagree	1 (3%)	7 (10%)	
q45-Residues of antibiotics can be found in milk	Agree	31 (97%)	59 (87%)	0.116
	Disagree	1 (3%)	9 (13%)	
q46-Residues of antibiotics can be found in eggs	Agree	26 (81%)	51 (75%)	0.488
	Disagree	6 (19%)	17 (25%)	
How is antibiotic resistance acquired				
q47-People can acquire resistance through consuming animal products that contain residues of antibiotics	True	31 (97%)	59 (87%)	0.231
	False	1 (3%)	4 (13%)	
q48-People can acquire resistance through direct bodily contact with sick animals	True	12 (37%)	32 (47%)	0.279
	False	20 (63%)	36 (53%)	
q49-People can acquire resistance through contact with animal feces	True	20 (62%)	43 (63%)	0.472
	False	12 (36%)	25 (34%)	
q50-People can acquire resistance through body fluids of sick animals	True	29 (91%)	57 (84%)	0.585
	False	3 (9%)	11 (16%)	
Withdrawal periods				
q53-Observance of withdrawal period makes the animal product safer for human consumption	Agree	31 (97%)	63 (94%)	0.086
	Disagree	1 (3%)	4 (6%)	

***significant at P < 0.05.*

such as Uganda, there inappropriate limited diagnostic facilities including antimicrobial sensitivity testing (10). Previous studies in Uganda by Dione et al. (17) and Ilukor and Birner (18) reported that incorrect diagnosis, under-dosing and overdosing and wrong drug administration routes, poor handling and storage of drugs were common practice among farm households and service providers in pig and cattle production systems, respectively. In fact, service providers were found not to be able to prescribe correct drugs for treatment of specific cattle diseases (18). Although the link between stakeholder practices

TABLE 8 | Factors associated with knowledge of veterinary practitioner about antibiotics and AMR.

Poisson regression	Number of obs. = 65
Wald chi2(9) = 48.58	Prob > chi2 = 0.0000
Pseudo R2 = 0.0374	Log pseudolikelihood = −122.00191

Variable	Coef.	Robust Std. Err.	z	P>z	[95% confidence interval]	
Determination of dosage by farmer						
Own judgment						
As indicated on the drug pack	0.092218	0.0528942	1.740	0.081	−0.01145	0.195889
Heard about AMR						
No*						
Yes	0.2543311	0.0922078	2.760	0.006**	0.073607	0.435055
Category of clients						
Small scale farms*						
Large scale farms	−0.1404909	0.0595735	−2.360	0.018**	−0.25725	−0.02373
Level of education of veterinary practitioners						
Primary*						
Diploma	0.0640564	0.06002	1.070	0.286	−0.05358	0.181693
BVM	0.119419	0.0726594	1.640	0.100	−0.02299	0.261829
Most important drugs in the business						
Antihelminthics*						
Antibiotics	−0.0215451	0.0625481	−0.340	0.731	−0.14414	0.101047
Arachnicides/vaccines	0.1090097	0.0792294	1.380	0.169	−0.04628	0.264297
District of operation						
Mukono*						
Lira	0.2139437	0.0693367	3.090	0.002**	0.078046	0.349841
Most frequent way of administering the drug to animals						
Whole course of treatment as recommended*						
Single dose/one-time application	−0.0347081	0.0525027	−0.660	0.509	−0.13761	0.068195
_cons	1.441464	0.0934914	15.420	0.000	1.258224	1.624704

**reference; **significant at P < 0.05.*

TABLE 9 | Actions needed to control AMR according to veterinary practitioners.

Variable	Category	Lira	Mukono
q55-I am conversant about the veterinary drug policy of Uganda	Agree	20 (63%)	19 (28%)
	Disagree	12 (37%)	49 (72%)
	Total	32 (100%)	68 (100%)
q59-Urgently needed to mitigate AMR	Knowledge on how to use AMs	8 (25%)	15 (22%)
	Understand mechanisms of AMR	6 (19%)	29 (43%)
	Knowledge on when to prescribe AMs	3 (9%)	5 (7%)
	Understand links between the health of humans, animals and the environment	5 (16%)	7 (10%)
	Understand the policies about the use of veterinary drugs in the country	10 (31%)	12 (18%)
	Total	32 (100%)	68 (100%)
q60-Critical actions for the sustainable control of AMR	Stronger and directed policies on AM use	10 (31%)	35 (52%)
	Raise awareness of farmers about the impact of AM misuse	13 (41%)	24 (35%)
	Strict monitoring of drug import into the country	2 (6%)	4 (6%)
	Re-enforce disease control in livestock	5 (16%)	1 (2%)
	Enhance disease diagnostic in livestock	0 (0%)	1 (2%)
	Strengthen quality control of drugs stocked in the country	2 (6%)	3 (4%)
	Total	36 (100%)	78 (100%)

and AMR is still weak, according to Ayukekbong et al. (10), the lack of appropriate quality control regulations as reported in the distribution of veterinary of drugs including antimicrobials could be a contributing factor to the misuse of antimicrobials; consequently, any imprudent practice along drug supply chain may fuel the emergence of resistance.

Pig/poultry and cattle farmers were the main customers of the drug, in Mukono and Lira districts, respectively. This can be explained by the difference in livestock production systems between the two districts: Lira district has a more rural production system with more cattle-farming, compared to Mukono which is characteristic of a peri-urban farming with increasing poultry and pig production. There was no market for antibiotics in small ruminant production in the studied districts. This could be explained by the fact that small ruminants are less market oriented; hence they are kept in low input systems with low investment of farmers on drugs and other inputs such as feed.

High awareness of veterinary practitioners about antibiotic residues in animal products and the importance of drug withdrawal time was reported in the study. However, it was not clear if practitioners advised farmers accordingly. The fact that there is lack of effective monitoring system for drug residues along the food supply chain in Uganda, makes it difficult to assess eventual risks to consumers. However, it is important to note that the profile of antibiotics reported in our study such as tetracyclines, sulfamidines and sulfamethoxazole-trimethoprim matches those of AMR reported in several studies in Uganda (19–21). Low resistance was reported in Uganda for the less commonly accessible antibiotics reported in our study such as ciprofloxacin and gentamicin (19, 21). Furthermore, another study (19) showed that AMR correlated negatively with the local price of the antibiotic, with the most expensive antibiotics (nalidixic acid and ciprofloxacin) showing near-zero resistance. These findings are in line with ours where accessible antibiotics are those that are said to be more affordable.

Awareness about AMR is an important factor identified for understanding the roles of antibiotics among veterinary practitioners, as is education. Both drug retailers and veterinary practitioners operate in an environment, which seems to be driven by financial profit, rather than quality of service to the end-users. This is aggravated by the low purchase capacity of farmers who aim to optimize investment for financial return from the farm. Therefore, quality of products seems not to be a focus, especially when regulators do not have a full hand on this. According to Byarugaba (4), the weaknesses in the implementation of policies are a challenge to sustainable drug resistance control and prevention of AMR as these laws exist only on paper or are poorly communicated to the stakeholders and also their implementation may be difficult due to poor funding. A possible underlying cause of this could be the lack or inadequate consultation when developing the policies. While the need for an improved policy environment of veterinary drug management is urgent, resulting policies and regulations should not undermine the business capacities of input suppliers, but the focus should be on increasing their knowledge on AMR and clearly defining their roles in supporting prevention of AMR.

CONCLUSION

Our study investigated the veterinary drug supply chain, the knowledge, practices, awareness and practices of veterinary practitioners on antimicrobial usage, and the related policy landscape. The common classes of antibiotics recorded in both districts were tetracyclines. Stakeholders of the drug supply chain pointed out lack of traceability of products as a major contributor to poor quality of drugs found in the market. Potential drivers of misuse of antibiotics, include low level of education of actors such as drug retailers, veterinary practitioners, poor handling of drugs at purchase and administration practices, low enforcement of policy and regulations and lack of awareness of stakeholders about policies that regulate use of drugs. Thus, future interventions to reduce misuse of drugs in small-scale livestock production systems should target improvement of the business of veterinary drug input suppliers, and deliberately involve a strong policy advocacy component.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Uganda National Committee for Scientific Technology with approval reference number A583. The patients/participants provided either their oral (informal interviews) or written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MD and BW conceived the study. MD, WCA, and BW developed the data collection tools. MD and WCA collected the data. MD analyzed the data and wrote the first draft of the manuscript. BW, EO, and FE made critical review and edits to the final draft. All authors contributed to the article and approved the submitted version.

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The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fvets.2021.611076/full#supplementary-material

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Farm and Livelihood Characteristics After ITM Vaccination Against East Coast Fever in Tanzania

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East Coast Fever is a critical cattle disease in East and Southern Africa which is currently mainly controlled through frequent chemical removal of ticks, the disease vector. However, a vaccine conveying life-long immunity has existed for some time, known as the infection and treatment method (ITM), although it has so far not been widely adopted because of its cost, demanding distribution system and regulatory reservations. Also, despite having proved effective on the animal level, the promoters of the vaccine have not been able to show much evidence of its benefits on the herd, farm and household levels. This study, based on a cross-sectional survey of 994 cattle keepers throughout Tanzania, aims to provide such evidence by comparing indicators of herd productivity, of farm management and success as well as of household livelihoods between households that have adopted the ITM vaccine for some years with those that have only recently adopted it. Econometric models identify the contribution of ITM adoption to indicator values together with various other determining factors amongst 277 long-term adopters of ITM and the control group of 118 recent adopters as well as 118 matched farmers without access to ITM. The results confirm that ITM adoption is positively associated with all three indicators of herd-productivity considered in this study. However, it does not support any of the three indicators of farm management and only one out of four indicators representing farm success. Nevertheless, the adoption of ITM shows a positive association with all four indicators of household livelihood. Investigating the chain of intermediate outcomes, indicators of herd productivity, such as milk yield, are significantly linked to higher feed expenses, contributing to increased livestock productivity and ultimately income and food availability. Overall, these results therefore support the promotion of ITM as a beneficial technology for the sustainable development of rural livestock keepers.

Keywords: vaccination, Tanzania, East Coast Fever, impacts, impact pathway

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INTRODUCTION

East Coast Fever (ECF), caused by the haemoprotozoan parasite Theileria parva and transmitted by ticks, causes considerable economic losses in 11 countries in Eastern, Southern and Central Africa. With about half of this region's 75 million cattle being at risk of ECF (1), losses caused by this disease are considerable, but quantitative assessments vary widely. For instance, in Tanzania the estimates of annual production losses due to ECF range from US$ 43 million [(2), cited by Ref.

(3)] to US$ 248 million (4). The disease causes high mortality (>80%) and affects high-grade dairy cattle (5) as well as young zebu cattle in pastoral production systems (3). Pastoralists are forced to avoid areas of high ECF risk, which is becoming increasingly difficult as the ticks and infected cattle move into new areas, driven by increasing land pressure, further spreading the disease (6). Current control measures involve the use of acaricides to prevent tick infestations in up to half-weekly intervals. However, even in areas where control measures are common, such as in smallholder dairy systems in the Dar-es-Salaam region of Tanzania, ECF prevalence rates of 45% and case fatality rates of 64% have been recorded (7). Besides these risks, an acaricide-based approach to ECF control implies considerable costs and negative environmental effects, calling into question the efficacy of this approach (8). Furthermore, after prolonged use of acaricides, ticks develop resistance to the chemicals. Effective drugs for the treatment of ECF are available but they require to be used at an early stage of the disease and are often too costly for poor livestock keepers, especially for the treatment of less valuable zebu cattle. Due to the ECF risks and the associated cost of controlling the disease, many smallholders across East Africa are reluctant to adopt improved breeds of cattle, as the disease affects Bos taurus breeds more severely than Bos indicus breeds (9), an effect common to many commercializing smallholder farming systems (10).

To find a more cost-effective control of ECF, an alternative approach, the infection and treatment method (ITM), was developed more than 40 years ago. Scientists from the East African Veterinary Research Organization (now the Kenya Agricultural and Livestock Research Organization), in collaboration with international partners had first reported life-long immunization against ECF by infecting and simultaneously treating cattle with a long-acting antibiotic in the mid-70s (11, 12). During these early stages of vaccine development, concerns among scientists, policy makers and veterinary authorities about the merits of the vaccine as well as a supply driven approach to vaccine distribution had limited the dissemination and adoption of ITM. The initial concerns were mainly based on the complexity of stabilate production, the widespread field use of over-the-counter antibiotics and the potential further transmission of the disease through ticks after vaccination with live pathogens (9, 13). Despite these reservations, ITM trials proceeded, improving and standardizing the vaccine (9) and demonstrating high rates of efficacy, above 95% in some cases (3, 14). Yet despite improved understanding of the pathogen und the vaccination-induced immune response (15), obstacles to wide-spread dissemination remained. These included the characteristics of the approach [animals are infected with live parasites of varying genetic identities (16)], distribution constraints (the vaccine requires liquid nitrogen storage), vaccination costs (US$ 8–12 per animal, including a dose of a long-acting specific antibiotic) and post-vaccination reactions (depending on vaccine and treatment doses some vaccinated animals show severe ECF infection symptoms). In addition, interests in the sale of acaricides have also affected the promotion of ITM (13). This resulted in lower than expected uptake during the first two decades of the vaccine's production (14).

To achieve the greatest benefits, the vaccination is mainly targeted at calves, thereby maximizing protection throughout an animal's life and reducing the amount of required antibiotics (9). In pastoral systems this was shown to decrease mortality by more than 90% (17), resulting in increased off-take of animals and more diversified investments by pastoralists. In addition, the same study reports that vaccinated animals, identified by their ear-tags, fetched higher prices at cattle markets. Furthermore, a trend toward improved cattle breeds has been reported where ITM has been adopted in extensive systems (18). In intensifying dairy systems, the use of the ITM vaccine allows farmers to quickly reduce the frequency of tick control (from weekly or twice weekly dipping/spraying regimes to once in 2 or 4 weeks, which is still required to control other tick-borne diseases) without any detrimental animal health effects (32), cited in Refs. (11, 14)]. The resulting reduction in production costs seems to be the main direct benefit in these systems. In addition, considerable gender differences have been detected, indicating significantly higher adoption rates within male-headed households (19).

Despite the high cost of ITM compared to other vaccines (3), it has been shown that controlling ECF with the ITM vaccine results in only about 60% of herd-level costs compared to treating clinically infected calves, without the consideration of subsequent tick-control activities. Kivaria et al. (8) report a 40–68% reduction in the annual cost of controlling ECF, depending on the post immunization dipping strategy adopted. The benefits of reducing acaricide use for tick control were also determined by Lynen et al. (14). Highlighting this aspect of private profitability, it has been proposed that strengthening the role of private sector animal health services within ITM distribution systems would be a more efficient approach to achieve wider adoption of the vaccine (9).

The current distribution model of the vaccine in Tanzania is composed of multiple actors. Mandated by the African Union (AU), the Center for Ticks and Tick-Borne Diseases (CTTBD) produces the ITM vaccine in Malawi for East and Southern Africa. Within Tanzania, the Director of Veterinary Services monitors and regulates the importation of the vaccine. There are currently four private companies who are licensed to import and distribute the vaccine; these are: PharmaVacs Ltd., Vetlife consultants Ltd., Dulle Veterinary Center and Ronheam International Ltd. These distributors sell the vaccine to trained vaccinators who are licensed by the Tanzania Veterinary Association and monitored by District Veterinary Officers. The vaccinators are engaged by farmers to vaccinate their cattle.

Most studies have limited the assessment of effects and costs of adopting ITM vaccination to the animal level (20, 21). Effects on herd productivity have hardly been determined (17). A simulation study of two smallholder farms in Kenya showed the positive economic effect of ITM on whole-farm economics, but only as an ex-ante assessment (22). Following a call for more poverty-oriented research into livestock diseases (23), a recent impact assessment study shows positive relationships between the adoption of ITM and milk yield, ECF mortality and various household development indicators; however, without quantifying the intermediate farm-level effects and controlling for differences between households with various degrees of ITM adoption through an instrumental variable approach (24).

While determining the effects of ITM vaccination on livelihood indicators is critical for assessing the value of this technology in contributing toward ultimate development objectives, this study also aims to better understand the pathways leading to these effects and which conditions are required to achieve them.

Accordingly, this study aims to:

- Assess how the adoption of ITM contributes to herd-productivity effects
- Determine how changes to farm management and success are linked to the adoption of ITM vaccination
- Identify differences in household-level livelihood indicators between long-term and recent adopters of ITM

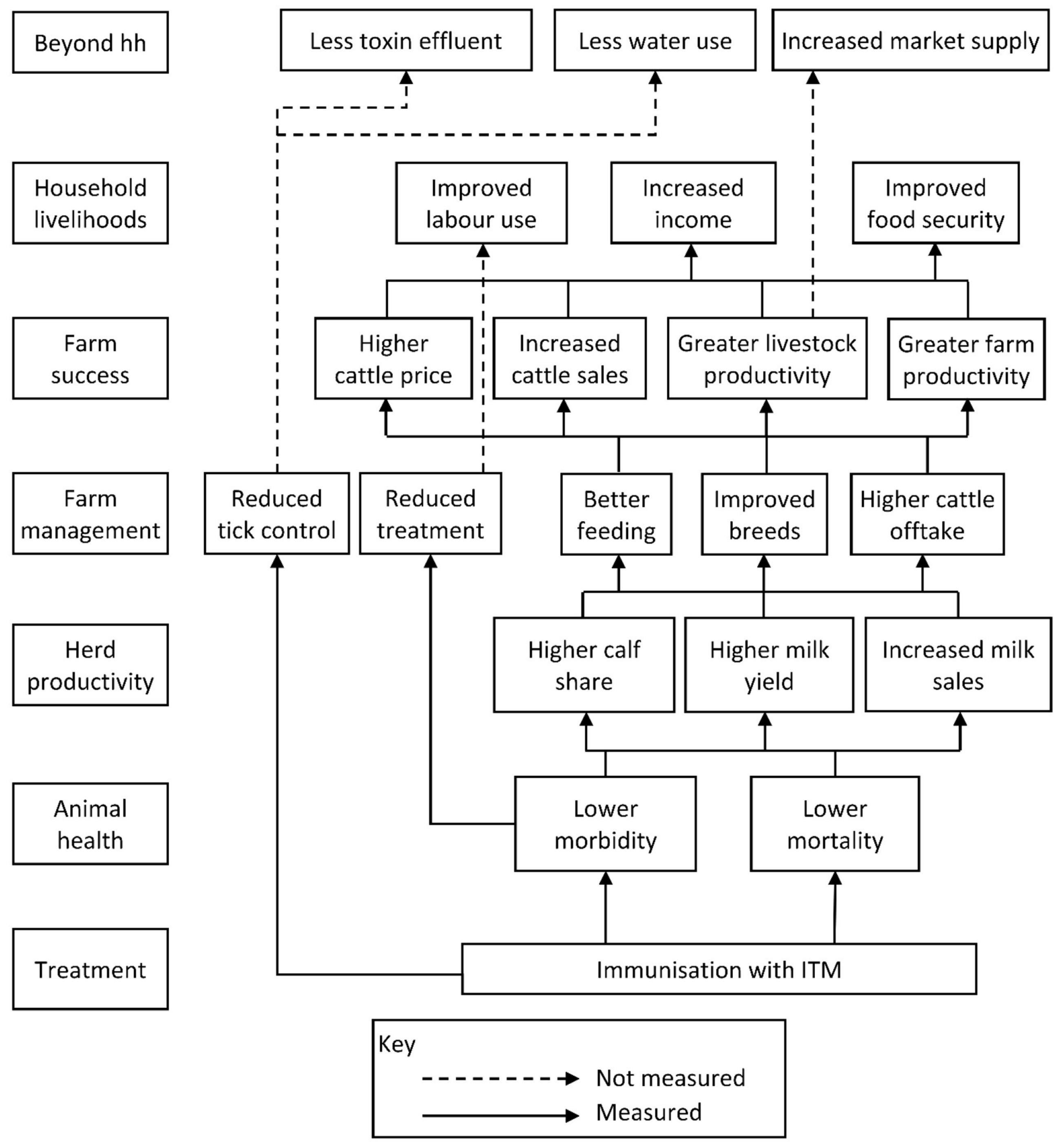

FIGURE 1 | The impact pathways of ITM vaccination and their consideration in this study.

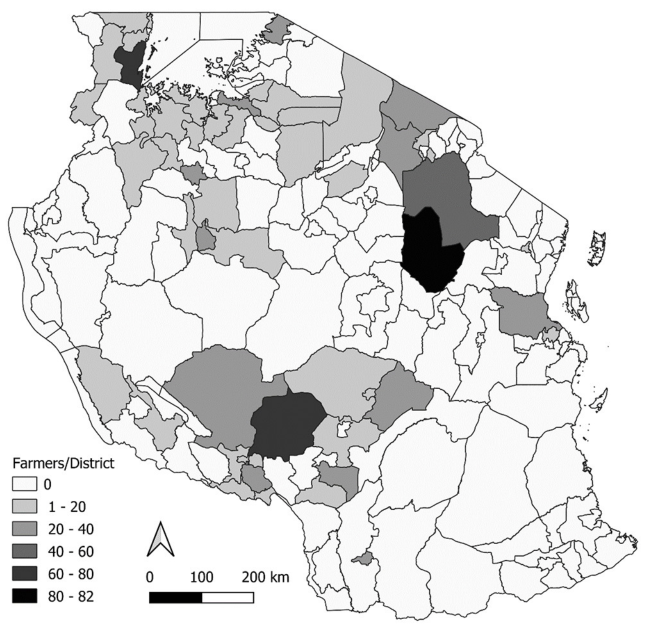

FIGURE 2 | Distribution of interviewed farmers within Tanzania.

MATERIALS AND METHODS

Conceptual Framework

ITM vaccination is assumed to directly affect herd productivity by reducing mortality and increasing milk production. Based on these effects, ITM vaccination is expected to stimulate improvements in farm management, further intensifying livestock production, for instance though advances in feeding and breeding practices. These are expected to lead to greater farm success, as measured for instance by the rate of cattle off-take and the average revenue of cattle sales. Greater farm success then allows for the improvement in household livelihood indicators for households with a strong dependency on livestock production. Such indicators include measures of income, poverty risk or food security. **Figure 1** presents the conceptual framework of the study, illustrating these pathways.

We aim to better understand the effects of ITM on farm households which have adopted this technology through the comparison of those households which have been applying the ITM vaccine to their cattle for a considerable time (the treatment group) to those which have not (the control group). To avoid self-selection bias, as would be the case when comparing vaccine adopters with those who have decided not to adopt, the control group is formed by farmers who have only recently decided to adopt the ITM vaccine, without the vaccine having yet been able to affect the health and productivity of their livestock. Because the number of farmers who had just started applying ITM was limited within the sample, additional control farmers were identified from those who had not had access to the ITM vaccine but showed similar characteristics to the recent adopters. This approach ensures a minimal selection bias as the farmers in both groups have voluntarily decided to adopt ITM, or have characteristics similar to adopters but have not had access to the vaccine.

Apart from determining the direct associations of ITM vaccination with various indicator variables, we also aim to better understand the pathways leading to these effects and the conditions required to achieve them, as illustrated in the conceptual framework. Therefore, we also investigate the links of intermediate outcomes with higher-level indicators.

Data

The data for this study were collected through a single-round survey of livestock farmers in Tanzania. The data were collected during August/September and November 2017 by a team of trained enumerators. The data collection tool was based on the RHoMIS instrument (26), extended to cover animal health interventions and herd dynamics in greater detail and implemented in ODK.

The selection of survey respondents was based on the contacts established with 331 ITM vaccinators and other animal health service (AHS) providers from all over the country through an ILRI-led ITM dissemination project. These service providers were asked to list the number of farmers they were serving in each of the following eight categories: long-term ITM farmers (i.e., ≥2 years of ITM adoption), just-starting ITM farmers (i.e., ≤12 months of ITM adoption), farmers not adopting ITM with ITM vaccinators and non-adopting farmers with non-ITM AHS providers, for both pastoralists and smallholder dairy producers. For each of these categories, 24 associated AHS providers (12 for non-adopters with ITM vaccinators) were randomly selected, emphasizing providers associated with fewer categories, thereby increasing the number of providers included in the study, and those operating in regions with at least three providers, thereby focusing on areas with greater density of cattle and livestock services. This resulted in a total of 118 AHS providers being randomly selected. These were then requested to list the contacts of 15 farmers per farmer category they were associated with, resulting in a sampling frame of 2,410 farmers. From this, six farmers per type and AHS provider were randomly selected for the survey. However, the initial approach of categorizing farmers into pastoralist and dairy production systems could not be pursued because only few farmers identified themselves as pastoralists.

In total, 994 farmers linked to 106 AHS providers were interviewed from across Tanzania (see **Figure 2**), including 277 long-term ITM adopters and 119 farmers that had just started vaccinating their cattle with ITM. The final survey sample also contained 325 farmers connected to AHS providers that did not offer ITM (see **Table 1**). Because the number of recent ITM adopters was far smaller than planned we applied propensity score matching (PSM) to additionally select similar farmers from the non-ITM AHS providers. This approach estimates propensity scores of group membership by logistic regression. These scores were then used to match the most similar farmers of the non-ITM farmers to the just-starting farmers. The variables included in the matching process were household size, age, gender and education level of household head, herd size per household member, cultivated land, enclosed grassland per cattle unit, feed

TABLE 1 | Survey data structure before and after propensity score matching.

Vaccinator ITM status	Farmer ITM status	Farmers interviewed	Farmers included after PSM[a]
Active	Long-term	277	277
Active	Just-started	119	118
Active	Inactive	273	0
Inactive	Inactive	325	118

[a]*PSM, Propensity Score Matching.*

expenses per cattle unit, market orientation and proportion of off-farm income. With this we were able to match 118 farmers from the inactive areas with the 118 recent adopters included in the analysis, resulting in a control group size of 236 farmers.

Methods

The research objectives mentioned above are achieved by econometric analysis of the farm-household data. Investigating the sub-samples of long-term and recent adopters of ITM, plus non-adopters matched with recent adopters by PSM, allows for the determination of the average effect of ITM vaccination on the treated (ATT) (25). The econometric analyses are based on selected indicator variables (i.e., dependent) which are then regressed on a selection of determinant variables (i.e., explanatory or independent). The indicators cover the domains herd productivity, farm management and success as well as household livelihoods, according to the conceptual framework introduced above. Herd productivity indicators include share of calves within cattle herds [calves per herd size, both measured in tropical livestock units (TLU)], milk yield (average daily milk production per herd TLU) and milk sales (milk sold per year and herd TLU). The indicators of farm management and success considered in this study include livestock management practices such as feed expenses (annual cattle feed purchases per herd TLU), keeping improved breeds (dummy variable characterizing main cattle breed type, with the responses "improved" and "mixed" categorized as "improved," contrasting with "local") and off-take rate (animals sold per herd size in animal numbers). The farm success indicators such as cattle price (annual cattle sales income per sold animal), average cattle sales revenue (annual cattle sales income per herd TLU), livestock productivity (value of all livestock products per herd TLU) and farm productivity (value of all crop and livestock products per area of cultivated land). Indicators linked to changes in animal health practices, such as treatment costs or acaricide control, could not be included in these analyses despite featuring in the conceptual framework because of the low number of responses to questions on these topics. Lastly, a collection of standardized indicators characterizes household livelihoods. These include gross per capita income, based on the total value of production and off-farm income per male adult equivalent (26), the Poverty Probability Index (PPI) (27), the Food Availability Index (26) and the Household Diet Diversity Score (28). The PPI, through a set of 10 questions customized for individual countries, generates a score value with which the probability of an individual household falling under a poverty line can be estimated. Within this study we use only the score value as a measure of poverty risk without actually calculating risk values. The Food Availability Index determines the calorific value of all farm products as well as of off-farm income (converted into food staples) per male adult equivalent. Finally, the Household Diet Diversity Score represents the number of food groups consumed by the household at least several times during the last week, out of a total of 10 food groups, based on the evidence that diet diversity is a robust indicator of diet quality and risk of malnutrition. Diet diversity data were collected for food scarce and food abundant seasons.

Apart from the treatment with the ITM vaccine, the econometric models also consider other variables expected to affect the indicator variables presented above. These cover various household, farm and herd characteristics and are listed below amongst the model details.

While the conceptual framework does not show two-way or feed-back relationships between practices and outcomes, it is obvious that these exist and that they may be critical in some cases. For instance, while the framework highlights the effects of productivity changes on behavior change in farm management, management practices clearly determine livestock productivity. The models consider this, by including management practices as determinants of herd productivity.

In addition to directly considering the ITM vaccination at several levels of analysis, a second set of econometric models investigates the intermediate outcomes along the impact pathway presented in the conceptual framework. To determine their contribution, they are included as determinants in the econometric models of the next level along the pathway. Accordingly, for this set of models, the direct ITM treatment variable is omitted to avoid overdetermination.

Initially, differences between treatment and control groups in outcome indicators and determinant variables are explored through independent sample *t*-tests of mean differences and chi-squared tests of association. The variation of the variables included in the results highlights the scope of further analysis. Subsequently, the association of ITM with various indicators is investigated by econometric analysis at the four levels of investigation: herd productivity, farm management, farm success and household livelihoods. All models apply ordinary least squares regression, except for the models determining the types of cattle breeds being kept, which are implemented with logistic regression due to the binary nature of the dependent variable. To avoid undue influence of exceptional observations on the results, the regression outputs were screened for influential observations, defined as being both outliers and having high leverage. Subsequently, three records were excluded from the herd and farm management level models and 6 records were excluded from the farm success and livelihood models.

Direct Investigation of ITM Effects

Modeling Effects on Herd Productivity

Herd productivity is characterized by three indicators: calf share in herd [%], daily milk yield (l/TLU) and annual milk sales (Tanzanian shillings (TZS) '000'/TLU). The association of ITM with herd productivity is estimated by the following empirical model:

$$Y_h = f(T_h, X_h) \tag{1}$$

Where subscript h denotes household. Y represents the set of dependent variables measuring herd productivity. The variable T reprents a treatment dummy (0 = control, 1 = treatment). Vector X is composed of independent variables that control for farm and household characteristics. These are household size (number of household members), age of household head (years), education of household head (0 = primary school level and lower, 1 = post-primary), gender of household head (0 = female, 1 = male), cattle herd size (TLU/household member), area of enclosed pasture (ha/TLU), annual feed expenses (TZS '000/TLU), cattle breed type (0 = local, 1 = improved), market orientation (% produce sold) and off-farm income share (% of total income). Interaction terms of ITM with herd size and market orientation are also included. Within all econometric models presented here, nearly all variables, both dependent and independent, are transformed to their natural log values, increasing the models' explanatory power.

Feed expenditure and breed-type have direct short-term effects on milk yield and are therefore considered as independent factors at the herd level. On the other hand, we expect management decisions on feed and breed to be influenced by herd-level productivity in the longer-term, as illustrated in the conceptual framework. Therefore, these variables are also included as dependent variables at the farm management level.

Modeling Effects on Farm Management and Success

Three variables are used as indicators of farm management practices: annual expenditure on feed (TZS '1000/TLU), main cattle breed type (0 = local, 1 = improved) and annual off-take rate (% animals sold). At the next level, four indicators characterize farm success: cattle price (TZS '000/sold animals), annual cattle sales revenue (TZS '000/herd TLU), livestock productivity ($/herd TLU) and farm productivity ($/ha). The production values are expressed in international $ converted by purchasing power parity (PPP). The links of ITM with farm management and success are estimated using the following empirical model:

$$P_h = f(T_h, X_h) \tag{2}$$

Here the subscript h denotes household and P represents the set of farm management and success indicator variables. Variable T reprents the ITM treatment dummy (0 = control, 1 = treatment) and X is a vector of independent variables that control for farm and household characteristics as defined for Equation 1 as well as interaction terms of ITM with herd size and market orientation.

Modeling Association With Livelihood Indicators

A total of four indicators are used as dependent variables for modeling household livelihood outcomes. These are: annual income per capita (int. PPP $/cap), poverty probability score (PPI score), daily food availability per male adult equivalent (kCal/MAE) and household diet diversity score (HDDS) in the food scarce season. The following empirical model was used to estimate the association of ITM with each of these indicators:

$$L_h = f(T_h, X_h) \tag{3}$$

Again, the subscript h denotes household, while L represents the set of livelihood indicator variables. Variable T represents the ITM treatment dummy (0 = control, 1 = treatment) and X is a vector of independent variables that control for household and farm characteristics as defined for Equation 1 and as well as several interaction terms.

The Contribution of Intermediate Outcomes

In an alternative approach to assessing the benefits of ITM we investigate the contribution of intermediate outcomes within the subsequent level of econometric modeling. These models have the same basic structure as the models on direct determination of ITM effects described above. However, instead of including the ITM treatment variable at each level, outcome variables of the previous level are included as determinants. Thus, the models investigating farm management practices contain the herd-productivity outcome variables: calf share, milk yield and milk sales. Similarly, the farm success models incorporate the farm management variables: feed expenses, breed type and off-take rate. Finally, the household livelihood estimations consider cattle sales price and revenue as well as livestock and farm productivity, the indicators of farm success. Interactions are not considered in these models.

RESULTS

The main categorization of survey respondents in view of assessing the ITM vaccination was by the year they started vaccinating. Among the 277 respondents categorized as long-term adopters, the earliest adoption was in 1998. However, the median year of adoption was 2014 and latest adoption was in 2015. Among the 118 just-starting adopters, all adoption had taken place between 2016 and 2017. Within the sample, most farmers had not vaccinated all their animals during the survey recall period of 12 months. Among those farmers for which data were available, long-term adopters had vaccinated 30% of their animals in the previous year ($n = 232$), while those who had just started had vaccinated 27% ($n = 100$).

Descriptive Statistics

To gain some insight into the distribution of variables considered in this analysis and into differences between the main categories we compare the treatment group (long-term ITM farmers) to the control group (just-starting farmers and matched non-ITM farmers). **Table 2** presents this comparison regarding variables

TABLE 2 | Descriptive statistics of dependent variables for ITM treatment and control groups.

Variable	Control *n* = 236		Treatment *n* = 277		*p*-value
	Mean	**SE**	**Mean**	**SE**	
Calf share [%]	7.99	0.70	9.35	0.65	0.16
Daily milk yield [l/TLU]	1.51	0.15	1.24	0.11	0.14
Annual milk sales [l/TLU]	391.70	41.29	336.68	32.44	0.30
Annual feed expenses [TZS '000/TLU]	56.89	5.74	32.32	4.05	0.00
Cattle breed type (improved = 1) [%]	63.14	3.15	46.21	3.00	0.00
Annual off-take [%]	11.89	1.41	13.79	2.03	0.44
Cattle sales price [TZS '000/sold #]	496.18	26.99	497.62	20.20	0.97
Annual cattle sales revenue [TZS '000/TLU]	171.09	19.50	183.66	39.14	0.77
Livestock productivity [$/TLU]	167.02	19.40	153.55	15.38	0.59
Farm productivity [$/ha]	2,656	725	3,143	1,070	0.71
Annual income [$/cap]	632.21	443.17	302.15	56.79	0.46
Poverty probability [PPI score]	20.66	1.34	27.15	1.54	0.00
Daily food availability [kCal/MAE]	14,848	7,413	39,477	30,027	0.43
Diet diversity [HDDS]	6.60	0.14	6.50	0.12	0.62

TLU, tropical livestock unit (cattle herd); cap, capita; TZS '000, USD 0.43; $, Annual production or income value in international $ converted by purchasing power parity; PPI, poverty probability index; MAE, male adult equivalent; HDDS, household diet diversity score, measured for food-scarce season.

TABLE 3 | Descriptive statistics of independent variables for ITM treatment and control groups.

Variable	Control *n* = 236		Treatment *n* = 277		p-value
	Mean	**SE**	**Mean**	**SE**	
Household size [members]	8.54	0.40	10.45	0.40	0.00
Age of household head [years]	50.10	0.76	50.56	0.66	0.65
Education of household head (post-primary education = 1) [%]	0.30	0.03	0.23	0.03	0.11
Gender of household head (male = 1) [%]	0.89	0.02	0.93	0.02	0.10
Farm size [ha]	5.30	1.71	7.01	0.73	0.36
Enclosed pasture [ha/TLU]	0.03	0.01	0.01	0.00	0.00
Herd size [TLU/cap]	2.84	0.37	6.54	0.70	0.00
Market orientation [%]	0.17	0.02	0.22	0.02	0.06
Off-farm income share [%]	0.17	0.02	0.15	0.02	0.36

TLU, tropical livestock unit (cattle herd); cap, capita.

which are expected to be dependent on the adoption of ITM, arranged by herd, farm and household levels. Results indicate that farmers in the treatment group on average showed a lower expenditure on animal feed and were less likely to keep improved breeds compared to the farmers in the control group. They also had a higher PPI score, appearing to be in greater danger of falling into poverty. The differences in means of other variables were not significant, either because the differences were small (e.g., cattle sales price) or because of large standard errors (e.g., food availability).

The second descriptive comparison between farmers in the treatment and control groups includes variables assumed to be independent of ITM adoption within the timescale covered by the study, but which are expected to be associated with the dependent variables presented above. The results, presented in **Table 3**, show several differences between the groups. While farmers in the treatment group have larger households, a greater livestock wealth per household member and are more market-oriented, farmers in the control group have more enclosed pasture per TLU, albeit at very low levels.

Directly Determined ITM Effects

Based on the study's design, a set of econometric models directly investigates the links of ITM adoption with indicators at herd, farm and household level, together with a collection of other determinant variables. **Table 4** presents the results regarding indicators of herd productivity. These models show positive and highly significant associations of ITM with all three productivity

TABLE 4 | ITM vaccination and indicators of herd productivity.

	Calf share [log(%)]	Daily milk yield [log(l/TLU)]	Annual milk sales [log(l/TLU)]
(Intercept)	0.83 (0.70)	−0.27 (0.37)	1.47 (1.58)
ITM status (long-term = 1)	0.22** (0.10)	0.20*** (0.06)	0.68*** (0.24)
Household size [log(members)]	0.18** (0.08)	−0.00 (0.04)	0.47*** (0.18)
Age of household head [log(years)]	0.14 (0.17)	0.07 (0.09)	−0.01 (0.39)
Education of household head (post-primary = 1)	0.08 (0.10)	0.06 (0.05)	0.20 (0.22)
Gender of household head (male = 1)	−0.22 (0.14)	0.13 (0.08)	0.22 (0.33)
Herd size [log(TLU/cap)]	0.23*** (0.05)	−0.05** (0.03)	0.36*** (0.11)
Enclosed pasture [ha/TLU]	−1.49** (0.59)	0.26 (0.32)	0.16 (1.34)
Annual feed expenses [log(TZS '000/TLU)]	0.08*** (0.02)	0.11*** (0.01)	0.31*** (0.06)
Cattle breed type (improved = 1)	−0.19 (0.12)	0.15** (0.06)	0.15 (0.27)
Market orientation [log(%)]	0.74** (0.29)	1.14*** (0.15)	4.62*** (0.65)
Off-farm income share [%]	0.17 (0.15)	0.17** (0.08)	0.71** (0.35)
ITM status * herd size	−0.14** (0.06)	−0.06* (0.03)	−0.52*** (0.13)
ITM status * market orientation	−0.02 (0.36)	−0.58*** (0.20)	−1.98** (0.83)
n	510	510	510
R squared	0.17	0.48	0.28
F statistic	7.73	35.11	14.97
P-value	0.00	0.00	0.00

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, capita.

TABLE 5 | ITM vaccination and indicators of farm management practices.

	Annual feed expenses [log (TZS '000/TLU)]	Cattle breed type (improved = 1) +	Annual off-take [log(%)]
(Intercept)	3.21** (1.27)	3.38 (2.52)	−0.13 (0.13)
ITM status (long-term = 1)	0.31 (0.19)	0.14 (0.36)	0.03 (0.02)
Household size [log(members)]	−0.84*** (0.14)	−1.35*** (0.26)	0.02 (0.01)
Age of household head [log(years)]	0.20 (0.32)	0.00 (0.63)	0.04 (0.03)
Education of household head (post-primary = 1)	0.28 (0.18)	0.96*** (0.32)	−0.01 (0.02)
Gender of household head (male = 1)	−0.42 (0.26)	−0.33 (0.51)	0.03 (0.03)
Herd size [log(TLU/cap)]	−0.80*** (0.08)	−1.33*** (0.16)	0.00 (0.01)
Enclosed pasture [ha/TLU]	−0.88 (1.13)	−0.18 (2.17)	0.25** (0.12)
Market orientation [log(%)]	2.36*** (0.51)	1.55 (0.94)	−0.05 (0.05)
Off-farm income share [%]	0.14 (0.29)	−0.14 (0.50)	0.05* (0.03)
ITM status * herd size	0.27*** (0.10)	0.03 (0.24)	−0.03** (0.01)
ITM status * market orientation	−1.61** (0.66)	1.49 (1.26)	0.02 (0.07)
n	510	510	510
R squared	0.39	–	0.04
F statistic	28.48	–	2.00
P-value	0.00	–	0.03

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); + Logit model: Pseudo R Squared = 0.482, Prob Chi^2 < 0.001; TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, capita.

measures: share of calves within cattle herds, daily milk yield and annual milk sales per livestock unit.

Among the other determinants, feed expenses and market orientation contribute positively to all three herd productivity indicators, while the negative interaction of ITM adoption and herd size indicates that the overall positive contribution of ITM is reduced in larger herds. The positive associations between ITM and milk yield and sales also seem to be reduced with increased market orientation, as indicated by the negative interactions. The contribution of other factors to herd productivity is more varied. Cattle herd size, measured in TLU per household member, and household size are positively associated with calf share and milk sales, while milk yields appear to be lower in larger herds. Off-farm income is positively linked to higher milk yield and sales.

TABLE 6 | ITM vaccination and indicators of farm success.

	Cattle sales price [log(TZS '000/sold #)]	Annual cattle sales revenue [log(TZS '000/TLU)]	Livestock productivity [log($/TLU)]	Farm productivity [log($/ha)]
(Intercept)	5.59*** (0.58)	4.11*** (1.13)	2.25* (1.22)	8.56*** (1.19)
ITM status (long-term = 1)	0.13 (0.09)	0.17 (0.17)	0.78*** (0.18)	0.17 (0.18)
Household size [log(members)]	−0.11* (0.06)	−0.14 (0.11)	0.25* (0.13)	0.30** (0.13)
Age of household head [log(years)]	0.20 (0.14)	0.28 (0.28)	0.00 (0.31)	−0.74** (0.30)
Education of household head (post-primary = 1)	0.06 (0.08)	0.14 (0.15)	0.04 (0.17)	−0.07 (0.16)
Gender of household head (male = 1)	−0.11 (0.14)	−0.09 (0.27)	−0.01 (0.26)	0.03 (0.26)
Herd size [log(TLU/cap)]	−0.07 * (0.04)	−0.52*** (0.08)	−0.06 (0.07)	−0.04 (0.07)
Enclosed pasture [ha/TLU]	0.25 (0.45)	2.37*** (0.86)	0.15 (1.00)	−1.22 (0.95)
Market orientation [log(%)]	0.58** (0.25)	0.38 (0.49)	5.61*** (0.49)	1.97*** (0.47)
Off-farm income share [%]	−0.03 (0.12)	−0.17 (0.23)	0.38 (0.27)	0.41 (0.26)
ITM status * herd size	0.02 (0.05)	−0.01 (0.09)	−0.36*** (0.10)	0.06 (0.10)
ITM status * market orientation	−0.38 (0.31)	−0.06 (0.59)	−2.11*** (0.63)	−0.72 (0.61)
n	275	275	507	486
R squared	0.09	0.42	0.37	0.08
F statistic	2.47	17.16	26.56	3.91
P-value	0.01	0.00	0.00	0.00

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, per capita; $, Annual production value in international $ converted by purchasing power parity.

The type of breed is negatively linked to calf share, while the share of enclosed pasture only shows a, negative, association with calf share.

On the farm level, the econometric models include the adoption of ITM in the estimation of farm management and farm success indicators. Regarding farm management, we consider expenditure on feed, the breed type of livestock being kept and the off-take rate, calculated as sold animals per size of herd, as indicators. The results presented in **Table 5** indicate no significant association of ITM vaccination with any of the three farm management indicators.

Of the other factors associated with improved farm management practices there seem to be more similarities in the determinants of feed expenses and breed type compared to off-take rate. Herd and household sizes show negative associations with the two former indicators, while market orientation has a positive coefficient only for feed expenses. In contrast, the off-take rate appears to be mainly linked to the share of enclosed pasture and of off-farm income.

The models investigating ITM adoption and farm success, shown in **Table 6**, include as dependent variables the average sales price and the average annual sales revenue of cattle, as well as livestock and farm productivity. Here, ITM adoption shows a significant contribution to livestock productivity only.

Among the other determinants included in these models, market orientation and household size are linked to the productivity indicators. The positive association of ITM with livestock productivity appears to be reduced by both herd size and market orientation. Sales revenue per animal being kept is reduced by herd size but increased by enclosed pasture. The cattle price appears to be mainly associated with market orientation.

Finally, the results of the direct association of ITM adoption with the livelihood indicators considered in this study, namely gross per capita income, poverty probability, food availability and household diet diversity, are shown in **Table 7**. The adoption of ITM shows significant contributions to all indicators with the expected signs; the negative sign for poverty probability indicates a reduced poverty risk. However, the positive associations of ITM, herd size and market orientation with livelihood indicators appear to be weaker when combined, as shown by their negative interaction terms in most cases.

Only market integration and off-farm income show strong positive contributions across all four livelihood indicators. Herd size is also positively linked to all livelihood indicators except for poverty probability. However, this indicator shows significant coefficients for household size, as well as age and education of household head, the latter negatively. Education is also associated with household diet diversity, though positively.

Effects of Intermediate Outcomes

In addition to considering ITM adoption directly at various levels of analysis, this study also attempts to follow the indirect outcomes linked to this technology along the pathways outlined in the conceptual framework illustrated above. For this, the outcome indicators at one level are included as determinants, i.e., independent variables, at the next level, instead of the ITM adoption variable. For consistency, these have been considered irrespective of whether they were significantly associated with ITM adoption or not.

The first such set of models investigates the contribution of herd productivity outcomes to farm management indicators. The results, presented in **Table 8**, show mixed associations. Milk yield

TABLE 7 | ITM vaccination and household livelihood indicators.

	Annual income [log($/cap)]	Poverty probability [log (PPI score)]	Daily food availability [log (kCal/MAE)]	Diet diversity [log(HDDS)]
(Intercept)	2.31** (1.01)	4.41*** (0.76)	8.46*** (1.04)	1.66*** (0.25)
ITM status (long-term = 1)	0.46*** (0.15)	−0.20* (0.12)	0.61*** (0.16)	0.09** (0.04)
Household size [log(members)]	0.21* (0.11)	0.74*** (0.09)	−0.17 (0.12)	−0.07** (0.03)
Age of household head [log(years)]	−0.61** (0.26)	−0.72*** (0.19)	−0.26 (0.26)	0.10 (0.06)
Education of household head (post-primary = 1)	−0.10 (0.14)	−0.72*** (0.11)	0.06 (0.14)	0.10*** (0.03)
Gender of household head (male = 1)	0.06 (0.22)	−0.11 (0.17)	0.16 (0.23)	−0.07 (0.05)
Herd size [log(TLU/cap)]	0.13** (0.06)	−0.00 (0.05)	0.33*** (0.06)	0.06*** (0.02)
Enclosed pasture [ha/TLU]	0.89 (0.87)	−0.02 (0.65)	−0.29 (0.89)	0.30 (0.22)
Market orientation [log(%)]	10.83*** (0.41)	−1.27*** (0.31)	2.99*** (0.42)	0.32*** (0.10)
Off-farm income share [%]	1.57*** (0.23)	−0.31* (0.17)	0.78*** (0.23)	0.15*** (0.06)
ITM status * herd size	−0.06 (0.08)	0.15** (0.06)	−0.19** (0.09)	−0.08*** (0.02)
ITM status * market orientation	−1.64*** (0.53)	0.65 (0.40)	−1.56*** (0.55)	−0.31** (0.13)
n	507	507	507	507
R squared	0.77	0.36	0.23	0.14
F statistic	147.07	25.49	13.41	7.21
P-value	0.00	0.00	0.00	0.00

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); TLU, tropical livestock unit (cattle herd); cap, per capita; $, Annual income value in international $ converted by purchasing power parity; PPI, poverty probability index; MAE, male adult equivalent; HDDS, household diet diversity score, measured for food scarce season.

TABLE 8 | Association of herd productivity with farm management indicators.

	Annual feed expenses [log (TZS '000/TLU)]	Cattle breed type (improved = 1) +	Annual off-take [log(%)]
(Intercept)	3.31*** (1.19)	4.49* (2.67)	−0.10 (0.13)
Calf share [log(%)]	0.09 (0.08)	−0.38* (0.20)	−0.00 (0.01)
Daily milk yield [log(l/TLU)]	1.80*** (0.24)	2.65*** (0.59)	0.02 (0.03)
Annual milk sales [log(TZS '000/TLU)]	−0.20*** (0.06)	−0.36*** (0.12)	−0.01 (0.01)
Household size [log(members)]	−0.58*** (0.13)	−1.06*** (0.27)	0.02 (0.01)
Age of household head [log(years)]	0.03 (0.30)	−0.18 (0.66)	0.04 (0.03)
Education of household head (post-primary = 1)	0.08 (0.16)	0.75** (0.33)	0.00 (0.02)
Gender of household head (male = 1)	−0.54** (0.25)	−0.40 (0.52)	0.03 (0.03)
Herd size [log(TLU/cap)]	−0.37*** (0.06)	−0.93*** (0.13)	−0.01 (0.01)
Enclosed pasture [ha/TLU]	−0.67 (1.05)	−1.34 (2.36)	0.20* (0.12)
Market orientation [log(%)]	0.27 (0.34)	1.90*** (0.69)	0.01 (0.04)
Off-farm income share [%]	−0.04 (0.27)	−0.36 (0.54)	0.06* (0.03)
n	510	510	510
R squared	0.47	–	0.04
F statistic	39.54	–	1.67
P-value	0.00	–	0.08

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); + Logit model: Pseudo R Squared = 0.517, Prob Chi^2 < 0.001; TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, capita.

and sales are closely associated with feed expenses and breed type, although the causality and the negative sign for milk sales remain to be discussed. Calf share only shows a negative association with breed type, indicating a higher calf share in herds with more local breeds. The model predicting off-take rate does not appear to be significant.

Beyond the herd productivity outcomes, household and herd size show negative links with feed and breed indicators in these models, but there is a positive contribution by market orientation to breed type. Also, female household heads appear to invest more in feeds while more educated household heads favor improved cattle breeds.

On the next level, the contribution of the farm management indicators to farm success are shown in **Table 9**. Here, feed expenses and off-take rate have significant positive links with livestock productivity. While off-take is also linked to sales

TABLE 9 | Association of farm management with farm success indicators.

	Cattle sales price [log(TZS '000/sold #)]	Annual cattle sales revenue [log(TZS '000/TLU)]	Livestock productivity [log($/TLU)]	Farm productivity [log($/ha)]
(Intercept)	5.72*** (0.59)	3.38*** (0.86)	2.00 (1.24)	8.17*** (1.20)
Annual feed expenses [log(TZS '000/TLU)]	−0.01 (0.02)	0.03 (0.03)	0.15*** (0.04)	0.03 (0.04)
Cattle breed type (improved = 1)	0.19** (0.09)	0.16 (0.12)	−0.01 (0.21)	0.33* (0.20)
Annual off-take [log(%)]	−0.10 (0.19)	3.84*** (0.27)	0.95** (0.40)	−0.76** (0.38)
Household size [log(members)]	−0.07 (0.06)	0.05 (0.09)	0.37** (0.14)	0.42*** (0.14)
Age of household head [log(years)]	0.15 (0.14)	0.12 (0.21)	−0.03 (0.31)	−0.73** (0.30)
Education of household head (post-primary = 1)	0.02 (0.08)	−0.03 (0.12)	0.09 (0.17)	−0.13 (0.16)
Gender of household head (male = 1)	−0.11 (0.14)	−0.28 (0.21)	−0.03 (0.26)	0.06 (0.25)
Herd size [log(TLU/cap)]	−0.03 (0.03)	−0.15*** (0.05)	−0.11* (0.07)	0.08 (0.06)
Enclosed pasture [ha/TLU]	0.14 (0.44)	0.95 (0.64)	−0.21 (1.00)	−1.07 (0.94)
Market orientation [log(%)]	0.30** (0.15)	0.35 (0.21)	4.37*** (0.33)	1.35*** (0.31)
Off-farm income share [%]	−0.03 (0.12)	−0.05 (0.17)	0.31 (0.27)	0.45* (0.26)
n	275	275	507	486
R squared	0.10	0.67	0.36	0.10
F statistic	2.59	48.93	25.09	4.63
P-value	0.00	0.00	0.00	0.00

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, capita; $, Annual production value in international $ converted by purchasing power parity.

revenue, breed type is, unsurprisingly, associated with higher cattle prices.

Household size and market orientation are significantly linked to increased livestock and farm productivity in these models. Smaller herds seem to imply higher average sales revenues and livestock productivity. Once again, off-farm income seems unrelated to farm success, except for farm productivity.

Finally, **Table 10** presents the contributions of farm success outcomes on livelihood indicators. Both livestock and farm productivity are strongly linked to increases in income and food availability. Cattle sales revenue, unsurprisingly, increases income, but is not linked to the other livelihood indicators, while the cattle price does not seem to show any significant associations. Diet diversity is not associated with any of the farm success indicators.

Off-farm income contributes significantly to all four livelihood indicators, positively. The only other significant determinants of diet diversity are smaller households and higher education. Market orientation is linked to improved income, poverty risk and food availability, while herd size is associated positively with income and food availability. Poverty probability is also decreased by smaller household size as well as by higher age and education of the household head.

DISCUSSION

In contrast to most studies on the ITM vaccine, which focus on restricted areas and on interventions targeted at specific communities or production systems, this study aims to provide representative insights into outcomes associated with ITM adoption within major cattle-keeping areas of Tanzania and where ITM has been promoted for many years. On the other hand, ITM adoption is not yet ubiquitous, which would have made the identification of a control group as a counterfactual very difficult. Therefore, the stage of the scaling process at which this study was implemented appears to have been appropriate. Nevertheless, finding enough eligible and collaborative animal health service providers and generating a sufficiently large and accurate sampling frame of farmers presented a challenge, especially when attempting to consider multiple distinct production systems, generally mentioned as a major characteristic when describing the Tanzanian livestock sector (29). However, because a simple categorization of systems, for instance into dairy and pastoralist farmers, could neither be achieved in the sampling frame nor in the collected data, this aspect was not considered. According to variables recording herd mobility, only very few respondents would have been characterized as pastoralists. Discussions with stakeholders suggested that the concept of pastoralism was sensitive at the time of the survey, with many administrative efforts aimed at restricting the movement of livestock. This is in line with other findings showing that livestock production systems in Tanzania are becoming less distinct with many pastoralists engaging in crop production and reducing their transhumance (30). Therefore, it appears justified not to consider this aspect explicitly in the current analysis, especially as production system characteristics, such as herd size, cultivated land or enclosed grazing area, are already included. Nevertheless, a better understanding of current production systems and their linkages with animal health management would be useful when investigating technology adoption patterns and their determinants. However, these research objectives are not

TABLE 10 | Association of farm success with household livelihood indicators.

	Annual income [log($/cap)]	Poverty probability [log (PPI score)]	Daily food availability [log (kCal/MAE)]	Diet diversity [log(HDDS)]
(Intercept)	−3.89** (1.59)	8.01*** (1.34)	3.51*** (1.31)	1.80*** (0.40)
Cattle sales price [log(TZS '000/sold #)]	−0.01 (0.17)	−0.18 (0.14)	0.04 (0.14)	−0.04 (0.04)
Annual cattle sales revenue [log(TZS '000/TLU)]	0.22** (0.09)	0.06 (0.07)	0.06 (0.07)	0.00 (0.02)
Livestock productivity [log($/TLU)]	0.34*** (0.06)	−0.08 (0.05)	0.23*** (0.05)	0.02 (0.02)
Farm productivity [log($/ha)]	0.23*** (0.06)	−0.09* (0.05)	0.43*** (0.05)	0.01 (0.01)
Household size [log(members)]	0.15 (0.13)	0.76*** (0.11)	−0.35*** (0.11)	−0.09*** (0.03)
Age of household head [log(years)]	0.05 (0.34)	−1.21*** (0.29)	0.06 (0.28)	0.11 (0.09)
Education of household head (post-primary = 1)	−0.10 (0.18)	−0.69*** (0.15)	0.21 (0.15)	0.10** (0.05)
Gender of household head (male = 1)	0.26 (0.32)	−0.19 (0.27)	0.39 (0.26)	−0.07 (0.08)
Herd size [log(TLU/cap)]	0.46*** (0.07)	0.09 (0.06)	0.42*** (0.06)	0.01 (0.02)
Enclosed pasture [ha/TLU]	0.63 (1.01)	−0.61 (0.84)	0.39 (0.82)	−0.12 (0.25)
Market orientation [log(%)]	8.97*** (0.40)	−0.74** (0.34)	0.73** (0.33)	0.06 (0.10)
Off-farm income share [%]	1.46*** (0.28)	−0.57** (0.23)	0.44* (0.23)	0.20*** (0.07)
n	261	261	261	261
R squared	0.82	0.43	0.59	0.16
F statistic	91.84	15.83	29.25	3.99
P-value	0.00	0.00	0.00	0.00

****p < 0.01; **p < 0.05; *p < 0.1.*
(Standard error); TLU, tropical livestock unit (cattle herd); TZS '000, USD 0.43; cap, capita; $, Annual income value in international $ converted by purchasing power parity; PPI, poverty probability index; MAE, male adult equivalent; HDDS, household diet diversity score, measured for food scarce season.

considered in this study and would require further and larger investigations. Also, the fact that the collected data could not accurately record animal health practices, especially regarding the control of ticks and the treatment of ECF, is a limitation of this study. It is often difficult to record individual, irregular farm management activities over a 12-month recall period, especially if they are associated with illness and death of animals. However, following the number of livestock keepers included in this study regularly throughout a 12-month period to record such data with shorter recall periods, for instance 30 days, would require substantially greater resources. The sampling approach for this study appears appropriate, although, had it been possible to identify more "just-starting" farmers, the number of additions from the group of non-adopters selected by propensity score matching would have been reduced. And a larger overall sample would have been better able to determine effects on variables with small differences between analysis groups, such as the cattle price. Finally, only a panel survey with a randomized application of the ITM vaccine would be able to overcome the uncertainty whether earlier adopters, defined here as "long-term" and considered as the treatment group, were not statistically different at the time of their ITM adoption to the more recent adopters, included in the study as "just-starting" and as the counter-factual. These differences between adopter types, building on Rogers' Diffusion of Innovation theory (31), could, for instance, apply to their risk behavior, innovation capacity, production intensity or livelihood indicators. However, even the "long-term" adopters in this sample might not represent typical early adopters in the sense of the innovation diffusion theory as most of them adopted ITM only 3 years prior to the survey while ITM had been available for nearly 30 years. Another bias could have occurred if the two groups had differed considerably in their production systems, even though the study could not effectively determine this. This would have been relevant, if, for instance, ITM had been targeted at some production systems earlier than others. The farm descriptives in **Table 3** do indicate some differences between groups, for instance in herd size and enclosed pasture. However, with farm size being indistinguishable, the two groups don't seem to differ considerably regarding their production system composition. Nevertheless, a credible counterfactual remains the basis for assuming causal relationships. Therefore, we refrain from interpreting the associations of ITM as impacts, which would imply causality. However, we are convinced that the various significant associations between the adoption of ITM and several relevant indicators provide valuable insights into the assessment of this important technology.

The results of the econometric models constructed according to the conceptual framework along hypothesized impact pathways vary considerable by the level of investigation. The adoption of the ITM vaccine is associated significantly and positively with the three herd productivity indicators. This is reassuring as these are the basis of most of the expected further benefits of ITM, apart from the reductions in the cost of tick control and ECF treatment. However, this study, with its focus on farm and household data, cannot determine the actual causes of the associations with milk yield and sales; whether they, for instance, result from more calves being available for stimulating lactation or because of improved cow health. Both causal links have been suggested. Nevertheless, the positive associations with ITM confirm various ex-ante and ex-post studies indicating the vaccine's benefits (3, 24). While feed expenses were associated significantly with all three herd productivity indicators, breed type appeared to be linked only to milk yield. The negative ITM—herd size interaction with all three indicators suggests that the productivity effect of ITM is higher in smaller herds. In general, it is assumed that smaller herds are more oriented toward dairy production and markets while larger herds resemble more extensive pastoral production systems. Changes in productivity might be easier and faster to determine, where milk is the main product and links to markets are stronger. This negative interaction contrasts with the general perception that farmers with larger herds are more eager to engage with vaccinators, partly because of the greater efficiency when vaccinating many animals at once. While the results indicate that ITM adoption offers considerable potential for improving reproduction and milk production in small herds, a more focused analysis would be necessary to comparatively determine the effects of ITM adoption in small and large herds and whether ITM might even lead to negative effects in some large herds.

However, the hypothesized changes to farm management practices, such as increased feed expenses, switching to improved breeds or a higher off-take rate, could not be determined. While the previous results had shown that more feed purchases increase herd productivity, the longer-term reverse causal link of ITM vaccination, representing a higher production potential, stimulating a greater use of feed inputs could not be detected. This also applies to the off-take rate and the share of herds with improved breeds, despite previous findings on changes in breed composition by ITM adopters (18). In addition, clearly differentiating animals of local breeds, which are often genetically mixed, from improved cross-bred animals is challenging in a survey situation. The included household characteristics, such as size, education and gender of head as well as market orientation appear to have greater influence on production intensification than ITM adoption within the period covered by this study.

On the other hand, ITM adoption does seem to have a positive link with livestock productivity, while the other measures of farm success appear to be unrelated. Any increases in cattle sales appear to be driven mainly by the off-take rate, which does not seem to be linked to ITM vaccination. That cattle prices are also not increased by ITM vaccination contrasts with various reports that ear-tags on marketed livestock indicating ITM vaccination result in a price premium. Among the other factors determining farm success, market orientation contributes most strongly, which is not surprising as farm success is mainly defined in market terms. Interestingly, average cattle sales revenue is not significantly associated with market orientation, as is the case with the off-take rate, which could be another indication of the importance of non-market production objectives in beef-oriented systems. That female-headed households appear to do better regarding cattle prices and farm productivity might warrant further investigation, but this is beyond the scope of this study.

Finally, the cumulative nature of benefits resulting from a specific intervention such as a livestock vaccine are highlighted in the positive effects of ITM adoption in all four livelihood-oriented models. This was not necessarily to be expected, as various other determinants might mask the influence of ITM on the livelihood indicators while moving through the levels of investigation from herd to household level. Nevertheless, it appears that the effects of ITM adoption on livestock productivity—and the importance of livestock—were strong enough to be significantly associated with livelihood improvements of the interviewed ITM adopters. However, it appears that the strength of ITM's benefits varies by type of farm household. For instance, farms with larger herds seem to see less improvements in food availability and diet diversity when adopting ITM, compared to those with smaller herds as shown by the significant interaction terms. A similar effect is seen regarding market orientation. This underlines the need for gaining a better understanding of how the impact pathways of ITM adoption differ amongst various types of livestock keepers and whether adopting ITM might even lead to detrimental effects of some farmers. These insights would also be relevant for investigating patterns of ITM adoption.

An alternative approach to studying the separate steps along the impact pathway in greater detail is to include the dependent variables of one level as independent variables at the next level. The results from assessing the association of herd-level indicators on farm management confirm the earlier findings in this study that improved herd productivity does not appear to support overall production intensification within the study's observation period. Rather, specific productivity outcomes show contrasting effects. For instance, increased calf share shows a negative association with breed type. Raising calves beyond replacement requirements might be unattractive in dairy systems, which is where improved breeds have mainly been introduced. On the other hand, higher milk yield is associated with production intensification. It is however challenging to interpret the negative coefficient of milk sales with feed expenses and breed type. Whether home consumption plays a sufficiently important role to explain the difference between yield and sales or whether a correlation with other determinants is at play is difficult to determine within this study.

At the next level, the beef-oriented pathway seems to again show the strongest linkage, with off-take rate associated with both cattle sales and overall livestock productivity, while feed expenses are only linked to livestock productivity increases. However, it must be acknowledged that potential direct contributions to livestock productivity by herd-level outcomes such as milk production and sales are not considered in these models. The negative association of off-take with whole farm productivity, which includes crop production and is calculated per farm area, is again most likely due to differences in farm characteristics and production orientation. Finally, out of the included farm success indicators both livestock and farm productivity significantly improve income and food availability. Diet diversity seems to be dominated by the availability of off-farm income in this model.

While these results confirm the beneficial effects of adopting ITM amongst a wide range of livestock farmers in Tanzania, questions remain regarding differences in magnitude and impact pathways amongst different farm households. It would be especially interesting to study the differences more intensively between dairy- and beef-oriented producers regarding the interlinked determinants of farm success and livelihood improvements. It appears that while the conceptual framework introduced in this study is useful for a basic understanding of potential impact pathways it does not sufficiently capture effects across several levels and within levels. For instance, the effect of milk sales on livestock productivity is obscured by the intermediate farm management practices. Also, it could be argued that food security is more directly dependent on income or poverty indicators rather than on farm success, implying the importance of impact links within the levels defined for this study. It would need further discussion to determine whether the greater clarity gained by grouping indicators into levels outweighs the drawbacks of missing out on perhaps crucial linkages within these levels. However, variables within the same levels might also be highly correlated, which would challenge the interpretation of results if included in the same model.

Despite the difficulties in identifying and quantifying the most relevant impact pathways within these farm households, this approach appears essential to gain a better understanding of how the ITM vaccination—and other interventions aimed at improving livestock productivity—cause livelihood improvements. Only then will it be possible to efficiently target dissemination activities, create supportive conditions and anticipate the effects of overall development trends.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Research Ethics Committee (IREC) International Livestock Research Institute (ILRI). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

NT led the design and implementation of the study as well as the development of the analysis and of the manuscript. LK supervised the survey implementation, implemented the analysis, and contributed to the manuscript. JH, MW, and HK contributed to the design of the study and the data collection tool as well as to the manuscript. All authors contributed to the article and approved the submitted version.

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