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Hair sheep in the Americas: economic traits and sustainable production

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The relevance of hair sheep and their place in animal agriculture in the United States is expanding. Fueled by the exigency of sustainable agricultural practices, the integration of hair sheep to replace their wool breed counterparts is essential. Approximately 10% of all sheep globally are hair sheep but they are growing in numbers and production each year. Hair sheep breeds are widely diverse but share a common origin in tropical countries. Most of the prominent breeds were mindfully developed and crossed with wool breeds (namely, the Mouflon sheep) to improve the economically important traits of the animal. This genetic development has proven successful; hair sheep are considered highly advantageous in carcass quality, meat taste, litter size, and leather quality. Aside from those economically important traits, hair sheep are also advantageous in production traits, such as parasitic resistance, disease resistance, heat tolerance, sperm quality, and nutritional efficiency. These identified traits of hair sheep are highly desirable and contribute to the hair sheep's positive reputation. However, hair sheep pose some disadvantages, such as an average or below average scrotal circumference, lower meat yield (although high in quality), meat with higher cholesterol than that of the wool breeds, and the lack of wool leaving the hair sheep susceptible to cold stress. These disadvantages can be mitigated with genetic selection and production techniques. The importance to further developing hair sheep is irrefutable. This review focuses on the fundamental and applied science of the most common hair sheep breeds and is expected to be useful for students, scientists, and producers of hair sheep.

KEYWORDS

carcass, genetics, parasites, reproduction, nutrition, efficiency, meat

1 Introduction

With the grand challenges of global warming and shrinkage of agricultural lands for livestock farming along with the increasing human population, there is an urgent need for efficient and sustainable production of food animals. From multi-species livestock farming to increased interest in mutton by the ethnic populations in the United States (US), sheep agriculture is becoming more relevant. With the reduced competitiveness and value of wool, hair sheep have become the desired breed as compared to wool sheep. Hair sheep production has enormous potential for the tropics and subtropical areas of the world, including the Southern US, where the warm and humid climates can easily be overcome by these resilient animals. Hair sheep can tolerate harsh conditions and rough feeds, of course, they will be more productive when conditions are improved, showing characteristics of fertility all year round (Fitzhugh and Bradford, 2018).

Hair sheep include a wide diversity of breeds that have their origins mainly in tropical countries. Fitzhugh and Bradford (2018) describe those from Western Africa, that arrived at the Americas through the transportation of slavery, and which were the starting point of new hair sheep breeds developed up to now, such as those from the US Saint Croix, Katahdin, Royal White, and American Black Belly; from Brazil Santa Ines, and Brazilian Somali; Barbados Black Belly from Barbados; Dorper from South Africa; Wiltshire Horn from southern England; Black Headed Persian from Somalia; Pelibuey from Cuba, similar to Tabasco from Mexico, and West African in Venezuela; Damara from Eastern Asia and Egypt; the Uda sheep from Chad, Niger, northern Cameroon, and northern Nigeria, among others. Most of these breeds were developed by crossing strictly hair sheep with some wool breeds to improve the conformation of these animals (Schoenian, 2021) which are also called composite hair sheep breeds (van der Merwe et al., 2019).

There is a need for more transformative and translational research owing to the advantages of hair sheep (Figure 1) in the production of food animals with economically important production traits. Although some research results along with anecdotal observations suggest significant advantages of hair sheep, there is also a need for more evidence-based new knowledge that can be used to advance fundamental and applied hair sheep science. This review focuses on the basic and applied science of the most common hair sheep breeds. With the advances in both science and technology including genomics and artificial intelligence, greener pastures seem to be ahead for precision agriculture of the sheep. The scientific resource is expected to be useful for students, and scientists to learn about and advance sheep science, and for producers to develop efficient and sustainable hair sheep farming.

2 Hair sheep and economically important production traits

2.1 Genetic composition

About 10% of the global sheep population is comprised of hair sheep breeds. All sheep breeds, hair, and wool can be traced back to the Mouflon sheep. With hair sheep breeds and wool sheep breeds sharing the same ancestral source, yet displaying starkly different phenotypes present-day, the genetic diversity of hair sheep today is immense (OSU, 2022). All sheep breeds yield 27 pairs of chromosomes, for a total of 54 chromosomes. These consistent numbers of chromosomes throughout all sheep breeds, wool, and

FIGURE 1
Hair sheep advantages & disadvantages. Pictured: Katahdin (top left) [Katahdin Haair Sheep International], Barbados Blackbelly (top right) [Oklahoma State University]. St. Croix (bottom left) [Oklahoma State Univeristy], and Dorper (bottom right) [American Dorper Sheep Breeder's Society].

hair alike, allow for genetic possibilities from crossbreeding and selection (Aaron, 2014).

The Barbados Blackbelly (BBB) hair sheep's origin can be traced back to Africa and the island of Barbados during the first quarter-century of colonization by Europeans. It is supported that the BBB evolved from the genetic influence of African hair sheep and European wool breeds. However, the wool sheep breed that influenced the development of the breed is unknown. The BBB was bred with its native tropical climate in mind. A sheep that produced quality mutton with a high tolerance to heat was desired and successfully developed through genetic selection. The BBB was introduced in the US by the United States Department of Agriculture (USDA) in 1904 (Shelton, 2018; OSU, 2022). Four ewes and one ram were imported at that time. The next most notable importation of the hair breed occurred in 1970 from Barbados to North Carolina State University. The genetic characteristics of this breed are excellent flavor and lean meat, parasite resistance, heat tolerance, and high ADG. Currently, the BBB sheep are few in North America. Reestablishing the breed in the US and continuing its development in mutton quality, heat tolerance, and parasite tolerance would be monumental (OSU, 2022).

According to Boyd (2018), BBB sheep arrived in central Mississippi in the early 1960s, coming from Texas. Later in the spring of 1971, these animals arrived at Mississippi State University (MSU). All animals were polled, weighing 75-95 pounds for the ewes and 132-150 pounds for the rams, all with the standard color pattern. In the same year, a group of Dorset ewes was introduced at MSU, and between 1972 and 1977, these breeds and their crosses were compared. The Dorper hair sheep breed was developed from the Dorset Horn (wool sheep) and Blackhead Persian (hair sheep) in South Africa's arid regions. The breed can display the phenotype of a characteristic blackhead (Dorper), or a whitehead (White Dorper), with overall distinct advantages such as high fertility, prolificacy, rapid growth rate, high weaning weight (an economically important trait of mutton sheep), an impressive ADG, and is highly adaptable to a wide range of climactic and forage conditions (OSU, 2022). Dorper was genetically selected to be hardy against unfavorable arid conditions. The development has delivered, and the breed has earned its position as a popular hair sheep. Crossbreeding efforts in research settings with the Dorper breed would be economically and genetically profitable for the small ruminant industry (OSU, 2022).

Katahdin sheep were developed in the US at the Piel Farm in north-central Maine. Michael Piel sought to develop a sheep breed that could be used to graze power lines instead of spraying or mowing the surrounding vegetation. He also selected for hair coat that did not require shearing, quality meat, high fertility, and flocking instinct. Piel purchased three "African Hair Sheep" from St. Croix in 1957 (KHSI, 2023). He crossed these three sheep with many different wool breeds, such as Southdown, Hampshire, and Suffolk. In the 1970s, Piel felt confident that he had achieved his goals; he selected 120 ewes from his flock and deemed them "Katahdin". Katahdin sheep have continued to be developed and genetically improved. They are characterized as being hardy, adaptable, low maintenance, parasite resistant, yield a lean carcass, and display exceptional mothering ability. Katahdin sheep are widely used in crossbreeding production systems. The phenotype of the first generation of Katahdin x wool sheep is wool fleece with hair interspersed. The characteristics of purebred Katahdin will be present about three generations later. The development of the Katahdin and Katahdin crossing holds the potential of increasing the genetic diversity of hair sheep populations, due to Katahdin's impressive repertoire of economically important and desirable traits (KHSI, 2023).

St. Croix sheep, also known as the Virgin Island White sheep, originated in the British Virgin Islands in the Caribbean. The hair sheep of West Africa are believed to have influenced this breed development; it is also theorized that the St. Croix is a cross between the Wiltshire Horn and the Criollo. In 1975, twenty-five St. Croix sheep were imported to the United States and settled at Utah State University. Those sheep became the basis of the genotypic and phenotypic presentation of the present-day St. Croix breed in the U.S. (Foote, 2018; SCHSIA, 2023). Both natural and human genetic selections have contributed to the characteristics for which the breed is known for, including climate adaptability, fertility, parasite resistance, and docility. The St. Croix possesses desirable adaptations for tropical and sub-tropical regions of the world, making them a sought-after breed for production programs. Crossbreeding selection programs involving St. Croix are expected to increase genetic diversity and may improve other sheep breeds' less desirable traits (SCHSIA, 2023).

2.2 Reproductive characteristics

Fecundity. Hair sheep breeds are reproductively desirable. Traditionally, sheep are seasonal short-day breeders when their reproductive behavior or fecundity is not interfered with by production tactics. However, hair sheep are observably prolific all-year-round breeders in their native, tropical, or subtropical environments. Conception and ovulation rates and breeding activity of hair sheep are reportedly higher year-round ("out-of-season") than their wool and wool crossbred counterparts (Wildeus, 1997). Hair sheep are more prolific than wool sheep, namely St. Croix. The St. Croix Hair Sheep International Association (SCHSIA, 2023) states the research findings of several universities. SCHSIA indicates based on gathered data that St. Croix ewes produce an average of 2.1 births per lambing episode. Triplets are common and quadruplets are occasional. St. Croix ovulates year-round and demonstrates excellent mothering ability. Ewe lambs can expect their first estrus at 7-8 months of age, allowing their age at first lambing to be as early as 12 months of age. Dystocia is uncommon in St. Croix because of the acute angle of the pelvis and croup. This anatomy of the St. Croix ewe allows for a high lamb survivability rate, considering that the main causes of lamb mortality include trauma induced by the birthing/parturition process (Dwyer and Lawrence, 2008). St. Croix's lambing rate ranges from 150 to 250%. The St. Croix is not the only reproductively desirable breed. Many of the most popular hair sheep breeds demonstrate excellent ewe reproductive traits.

Fertility. The most important reproductive traits in sheep are ovulation rate or fertility (number of ova produced in one ovulation) and litter size (number of lambs born at parturition) (Abdoli et al., 2016). Litter size is important in the sheep industry, and ewes bearing multiples (twins and triplets, most commonly) are highly desirable. Other reproductive traits of sheep include birth weight and weaning weight. The heritability of reproductive traits is low, however, the opportunities to increase ovulation rates in sheep are promising with accurate genetic management and the involvement of polygenic breed differences (Notter, 2008). Crossbreeding sheep with proven desirable ovulation rates and litter rates with other breeds yielding non-desirable traits is recorded to be successful.

The BBB breeds year-round and presents a lambing interval of 6-8 months and a lambing rate of 150 to 230% per lambing. The Dorper has an extended breeding season with a lambing interval capability of 8 months and an average lambing rate of 150%. The Katahdin also has an extended breeding season, but a lambing interval of 8-12 months and a lambing rate of approximately 125% (Bactawar, 2018). According to Boyd (2018), during 4 years of evaluation in Mississippi, BBB, and BBB x Dorset (D) had 4.4 lambing while D had only 3.1. This could be explained by the fact that most of the hair sheep and crosses are not seasonal reproductive animals. Table 1 shows the superior reproductive performance of BBB sheep compared to BBB x D and D ewes in Mississippi. (Boyd, 2018) also highlights that the survival rate for BBB lambs was higher than for the other breeds, despite the larger litter size. However, the individual lamb weight at weaning was lower for the BBB group, but the total weight of lambs per lambing was higher for BBB (23.8 kg *vs.* 21.6 and 25.8 kg for Dorset, and BBB x D, respectively).

Chay-Canul et al. (2019) described the importance of the preweaning stage on meat production in Pelibuey and Katahdin and compared the litter size and performance of their lambs during the preweaning stage. The authors reported that even when the Katahdin had heavier lambs at birth and higher milk production than the Pelibuey ewes, both had similar litter-weaning weights. Contrary to this, (Nasrat et al., 2016) studied Pelibuey, Katahdin, Dorper, BBB, and their crosses, and reported no differences due to heterosis when comparing pure breeds *vs.* crosses. However, in this study, Katahdin ewes both lambed and weaned heavier offspring compared to the other pure breeds.

TABLE 1 Productive performance of Barbados Blackbelly (BBB) ewes, Dorset ewes, and crosses exposed to Suffolk rams in Mississippi, US.

Breeds	Barbados Black Belly (BBB)	BBB x Dorset	Dorset
Ewes lambing	66	61	47
Lambs born	112	90	60
Lambs weaned	109	86	52
Average litter size (born)	1.7	1.48	1.28
Average litter size (weaned, 60 days)	1.65	1.41	1.11

Modified from Boyd (2018).

St. Croix ram lambs reach puberty at around three months of age (SCHSIA, 2023), and are very active breeders (Foote, 2018). In a study conducted in Mexico to evaluate the reproductive parameters of St. Croix ram lambs, the scrotal circumference (SC) of the ram lambs ranged from 30 to 32 cm (Sanchez-Davila et al., 2020). According to Katahdin Hair Sheep International, Katahdin rams display early puberty, are aggressive breeders, display year-round fertility, and can successfully sire many ewes in their first exposure. According to research aimed at determining the reproductive characteristics of mature hair sheep rams, the average SC of BBB, Dorper, and Katahdin was 32.68 ± 0.28, 34.65 ± 0.25, and 35.03 ± 0.26, respectively (Cárdenas-Gallegos et al., 2012). According to this study, BBB rams produced the lowest percentage of abnormal sperm (4.70% ± 1.47), compared to Dorper rams (12.48% ± 1.31) and Katahdin (10.71% ± 1.35). The ejaculate volumes (EV, ml) for BBB, Dorper, and Katahdin were 0.52 ± 0.04, 0.64 ± 0.04, and 0.60 ± 0.04, respectively (Cárdenas-Gallegos et al., 2012).

Scrotal circumference and ejaculate volume are both positively correlated with desirable reproductive capabilities. The percentage of abnormal sperm is negatively correlated with desirable reproductive capabilities. It is universally recommended that mature rams, wool, and hair alike, have a minimum SC of 33 cm during the breeding season. The SC can decrease by 2 to 3 cm when the ram is not in its peak breeding season (Pezzanite et al., 2023). According to these authors from Purdue University's scrotal circumference reference chart for rams, SC > 35 cm in a ram >14 months of age ranks in the "excellent" class. Katahdin rams rank in the excellent category. Dorper rams rank "satisfactory" with their average SC of 34.65 ± 0.25. BBB, however, with an average SC of 32.68 ± 0.28 falls in the "questionable" category of this chart. The study on St. Croix ram lambs measuring the average SC ranging from 30 – 32 cm would also place them in the "questionable" category. These studies and comparing their results to the SC reference chart together can indicate that hair sheep rams may demonstrate an average or lower-than-average scrotal circumference. Libido and sexual behavior in BBB, Dorper, and Katahdin rams were evaluated at the Universidad Autónoma de Yucatán. The researchers observed the following sexual activities: anogenital sniffing, the flehmen response, foreleg kicks, number of mounts, and number of mating sessions. All hair sheep rams reportedly exhibited a full repertory of sexual behavior. Dorper rams showed a lower number of sexual activities than the other breeds apart from the number of mounts. However, the BBB and Katahdin rams demonstrated high sexual performance potential (Cárdenas-Gallegos et al., 2012).

2.3 Nutritional efficiency

Most of the nutritional requirements are calculated based on wool breeds in the case of sheep or from traditional dairy and meat breeds in the case of goats, which are different from those requirements for hair sheep (Oliveira et al., 2018). This means that the body weight, size, and daily weight gain are different between hair sheep or the tropical meat and dairy goats, all of which influence any estimates for research and production systems (Herbster et al., 2020). These authors established the relationship between body weight, fasting body weight, empty body weight, average daily gain, and empty body weight gain using Brazilian sheep breeds and generating new equations for hair sheep breeds such as Santa Ines, Morada Nova, and Brazilian Somali. Pereira et al. (2014) demonstrated that the maintenance net energy (NE) requirements for Brazilian Somali lambs were similar to the values used by the US nutritional systems. However, these values were lower than the requirements from ARC and the Commonwealth Scientific and Industrial Research Organization. In a different study also using Brazilian hair sheep breeds, the authors concluded that the nutritional requirements of two different hair sheep breeds were different from those found in the tables for international requirements (Costa et al., 2018). The production of hair sheep using the nutritional requirements of wool sheep shown in Table 1 decreases the efficiency of converting nutrients into products. The more adjusted these nutritional requirements are, the higher the economic return in these production systems. If instead of meeting the requirements or being above, they are not met, these hair sheep breeds can be more susceptible to parasites and diseases (McManus et al., 2020). It is suggested to develop nutritional guidelines specifically for hair sheep.

Hair sheep are also more productive under low-quality fibrous diets. (Silva et al., 2004) reported that Santa Inês hair lambs were more efficient using increasing levels of low-quality diets than F1 Ideal × Ile de France wool lambs. When comparing hair sheep breeds fed with moderate quality feed such as alfalfa hay, Wildeus et al. (2007) found that different hair sheep breeds, although had similar dry matter intake, can show different performances depending on their improvement. These authors found that Katahdin did not express a higher growth potential compared to St. Croix and BBB lambs.

2.4 Meat production

The goal of hair sheep production is mainly for meat, and the initial requirement for efficient meat production is the efficient growth of the animals. Macías-Cruz et al. (2009) studied differences in the preweaning characteristics of lambs from different sire breeds (Pelibuey, Dorper, and Katahdin). Pelibuey ewes in the confinement system had better reproductive efficiency, preweaning traits, and heavier litters when crossed with Dorper and Katahdin sires than with the Pelibuey sire. This is an expected outcome because Pelibuey is a 100% African hair sheep breed. Katahdin and Dorper are breeds genetically improved through the crossing of African and wool sheep breeds or composite breeds. The higher efficiency for meat production is based on the heterosis expressed by these crosses, but for these genotypes to be expressed, the environmental conditions need to be adequate.

Most hair sheep breeds are for meat production, important traits for this product are the loin eye area (LEA), the marbling score of the loin eye (MLE), the subcutaneous fat thickness (SFT), and leg circumference (LEC). Sena et al. (2020) found that the heritability for Santa Inês sheep of these traits, was within low to moderate, indicating the possibility of genetic selection for improving carcass yield and quality. The parameters and genetic breeding values were improved after the inclusion of genomic information on genetic breeding values for all the traits. These findings will contribute to increasing the rates of genetic progress per time unit. The muscularity and carcass fat deposition traits evaluated need to be considered simultaneously in a selection index to avoid undesired genetic gains.

Related to the carcass and meat quality, (Bunch et al., 2004) compared hair sheep *vs.* wool sheep and crosses and reported that wool sheep and crosses had significantly heavier carcasses and higher weight of wholesale cuts and loin eye depth, at the same time had lower levels of back fat and cholesterol. However, Boyd (2018) when comparing carcass traits of Suffolk-sired lambs from Barbados Blackbelly (BBB) ewes, Dorset ewes, and crosses in Mississippi, found a lower quality grade for the BBB carcasses, with lower leg score and loin eye area.

For the sensory evaluations, the hair sheep meat was preferred when directly compared with the same cuts of meat of the wool breeds despite the higher content of cholesterol and lower yield. (Issakowicz et al., 2014) found that hair lambs (Morada Nova and Santa Ines) and wool lambs (1/2 Ile de France x 1/2 Texel) did not differ in hot and cold carcass yields, however, conformation scores were higher for wool lambs compared to hair lambs. Overall, the wool lambs had a higher proportion of valuable meat parts such as leg, shoulder, rack, and ribs compared to the hair lambs and more luminosity of the meat. Also, Camacho et al. (2016) studied wool sheep meat (WSM) *vs.* hair sheep meat (HSM) from Canary Islands animals. The study concluded that the WSM had more red color than the HSM, as well as a higher water-holding capacity, shear force, intramuscular fat content, and MUFA (monounsaturated fatty acids). However, the HSM had a higher content of protein, ash, and PUFA (polyunsaturated fatty acids).

According to the final consumer's preference, wool, and hair sheep meats were compared in a recent study (Alanís et al., 2022) where 332 people surveyed from Mexico showed that 78% of the consumers preferred the traditional Mexican Barbacoa (BBQ) made from wool breeds (such as Rambouillet, Hampshire, Dorset, Suffolk, and Creole) *vs.* only 19% who preferred the flavor from hair sheep breeds (Katahdin, Blackbelly, Pelibuey, and Dorper).

2.5 Tolerance to heat stress

Hair sheep are produced around the world in dramatically different regions. Sheep production is a major agricultural industry in the Middle East, as well as in various regions of South, Central, and North America. Climate has a direct impact on animal health and productivity, and hair sheep must adapt to ensure survival and furthermore achieve production efficiency (Seixas et al., 2017). Hair sheep can have difficulties in fully adapting to higher temperatures and can undergo heat stress as studied in Santa Ineês and Morada Nova sheep. Heat stress is an imbalance between thermogenesis and thermolysis within the animal's body that disrupts homeostasis. Heat stress is especially prevalent in tropical and sub-tropical regions where the summer weather is marked by high temperatures and extreme humidity. The higher the environmental temperature-humidity index (THI), the more difficult it is for animals to maintain a homeostatic temperature (Pulido-Rodríguez et al., 2021). Hair sheep notably have a higher heat tolerance, but chronic heat stress remains a limiting factor in production (Li et al., 2018).

Generally, sheep have a thermal comfort zone between 15 and 30°C (Gesualdi-Junior et al., 2014). Sheep begin to experience heat stress in temperatures above this range. However, there are variations within sheep that determine how well the animal will adapt to heat stress. Breed, fat distribution, size, coat type, coat color, skin color, and morphometrics are all factors that will determine how well an animal can adapt to the environment (McManus et al., 2020). For example, sheep with longer legs dissipate heat more rapidly, and sheep with smaller bodies also experience a faster dissipation of heat compared to their counterparts. Larger-bodied sheep were observed to have higher rectal temperatures in a 2017 study. It was concluded that a higher rectal temperature indicated a lower adaptation to heat (Seixas et al., 2017), as seen in other livestock species.

Additionally, skin color and hair/coat color affect a sheep's ability to adapt to environmental heat stress (Gesualdi-Junior et al., 2014). The hair of a hair sheep allows for better protection from radiation, facilitates heat convection, and improves evaporative heat loss (Pulido-Rodríguez et al., 2021) compared to wool sheep. However, there is disagreement regarding if coat color influences heat tolerance. In a 2017 study on heat tolerance in Brazilian sheep, it was concluded that sheep with darker coats had less tolerance to heat, as their rectal temperatures were higher. It was hypothesized that a lighter coat reflects the sun, preventing large amounts of heat absorption (Seixas et al., 2017).

To combat heat stress, sheep often make behavioral and physiological changes in an attempt to lower their core body temperature. Heat stress has a direct correlation to reduced feed intake at any time of the day. This behavioral modification is commonly seen in the afternoons when the temperature is the highest (Gesualdi-Junior et al., 2014). Reducing steps and spending more time lying down are often observed in hair sheep, and other livestock, to combat heat stress. During the night, sheep have unique means of cooling themselves. They attempt to dissipate as much heat as possible while the temperature is lower. This allows their body to absorb and store more heat during the day to lessen heat stress (Pulido-Rodríguez et al., 2021). The lower nightly temperatures observed in some sub-tropical regions allow animals to feel relief from the heat stress endured during the day (Seixas et al., 2017).

Panting increases respiration rate as temperature levels rise. Panting is a behavior that allows for evaporative cooling. It is considered one of the most important behavioral cues of heat stress. It is hypothesized that to conserve water during heat stress, panting is preferred to sweating (Pulido-Rodríguez et al., 2021). Behavioral changes often are accompanied by related physiological changes. Unconsciously, the body begins to make physiological changes to regain homeostasis. In the early stages of heat stress, cortisol levels are important because cortisol is a hormone that is a direct representation of stress levels in the body. Under short-term heat stress, cortisol levels remain high, as the animals are under high amounts of stress. But as sheep begin to adapt, the levels of cortisol in the blood begin to drop. This is an indication that sheep can adapt to chronic heat stress (Pulido-Rodríguez et al., 2021).

Physiologically, sheep use vasodilation to increase blood flow to the skin to allow for heat to dissipate as it flows heat away from vital organs (Li et al., 2018). If this is not enough, the animal will take secondary measures, such as panting, to cool itself. Respiration rate, heart rate, and rectal temperatures are key indicators of heat stress. The respiration rate increases as heat levels rise. Higher respiration leads to increased heat dissipation. Heart rate, however, has an inverse relationship with heat stress. As heat stress increases, it has been noted that heart rate decreases. Lower heart rate can be attributed to reduced movements. When grazing is reduced, digestion is reduced as well. When grazing and digestion are reduced, they are not getting as many nutrients as their body may require. Decreased nutrients in the body can lead to a decrease in performance (Seixas et al., 2017). Regardless of reduced feed intake, heat stress lowers metabolic rates in sheep as well. Liver function has also been noted to decrease and oxidative damage to increase in the heat-stressed body.

Chronic heat stress also has a negative effect on hormones within the body. Thyroid hormones Th1 and Th2 have a balanced ratio and are essential to immune system function. Under heat stress, the balance is skewed. Heat stress causes an upregulation of Th2 and a downregulation of Th1, which suppress cell-mediated immunity. Other essential hormones disrupted by heat stress include prolactin, growth hormone, and follicle-stimulating hormone (McManus et al., 2020). Reproduction is a physiological process that is severely impacted by heat stress. When under stress, the desire to mate is hindered. In ewes, reproductive hormones are suppressed, and ewes can fail to exhibit estrus, which can lead to delayed ovulation. There is also evidence that heat stress causes higher rates of embryonic death in early pregnancy. For the ewes that carry to full term under heat stress, they are more likely to have lambs with smaller birth weights (Burke, 2005). In rams, heat stress can disrupt sperm production and quality, causing limited motility and morphological damage (Goode et al., 2018; McManus et al., 2020).

Hair sheep demonstrate a well-developed ability to tolerate heat in tropical and subtropical regions. Their resiliency to THI and environmental heat stress allows them to maintain productive efficiency in even the harshest of environments.

2.6 Tolerance to diseases & parasites

Throughout the history of sheep production, sheep have evolved with improved resiliency and resistance to infectious diseases and parasitic infestations. Resilience is defined as the capacity of an animal to remain healthy even when disease or parasitic levels in the body are high. Resistance is defined as the ability to prevent and reduce infections within the animal's body. Genetic selection for resistance and resilience is key for researchers and producers alike. Selection for this resistance, along with outside disease and parasite control, is an effective way to prevent diseases in sheep. Although hair sheep can still develop the same diseases as wool sheep, hair sheep are more resistant to both disease and parasitic infection than wool sheep. Developing effective selection and management methods to maximize resistance and resilience to disease and parasitic infection is key to increasing production.

Parasitic infestation is the number one cause of loss of production and fertility in sheep farming (Barbosa-Toscano et al., 2019). *H. contortus* is the main parasite of concern, this is a nematode that feeds on the blood of its host. Infestation with this nematode causes anemia, diarrhea, and hypoproteinemia (Cruz-Tamayo et al., 2021). High infestation levels in animals lead to high mortality levels. Antiparasitic drugs can be effective, but are costly and non-guaranteed, as the anthelmintic resistance status has grown globally.

In tropical areas such as Brazil, sheep farming is vital to the economy. This is especially true in the northeastern region of Brazil, where there is a long drought period along with three to five months of rain. The rainy season allows parasites to thrive. Traditional methods of parasitic control such as oral deworming are effective initially. Due to the wrongful use of antiparasitic drugs, however, antiparasitic resistance in *H. contortus* has increased dramatically (Barbosa-Toscano et al., 2019). Scientists are searching for methods of non-chemical parasitic controls to counteract increased. *H. contortus* antiparasitic drug resistance, including genetic selection (Teixeira et al., 2019). The Morada Nova sheep are native to this region of Brazil and have over time developed a genetic resistance to parasitic populations in the region through genetic selection. The natural genetic resistance has made it easier for producers to prevent and treat the parasitic populations as the natural resistance is boosted by the anthelminthic treatments given. The natural resistance also allows for fewer drugs to be used, reducing antiparasitic drug resistance in the population (Barbosa-Toscano et al., 2019).

When comparing hair and wool sheep and their resistance to parasites Bowdridge et al. (2015) have found that hair lambs infected with *H. contortus* have a significantly higher production of immunoglobulin A than infected wool lambs, which can be related to better immunity against parasite infection.

In Australia and South America, the Barbervax/Wirevax vaccine has been employed to control antiparasitic resistance, but the vaccine was never tested in a tropical region like Brazil. The vaccine works using hidden antigens from the extraction of antigens found in the digestive tract of adult *H. contortus* nematodes and formulating them into a vaccination. Once injected, the hidden antigens neutralize enzymes needed for digestion in adult *H. contortus* without interacting with the host sheep's immune system (Teixeira et al., 2019). The vaccine was studied in the northeastern region of Brazil on a flock of Santa Ineês cross-bred sheep, which are the most common breed in that region. Once the vaccine was employed, researchers discovered a reduction in fecal egg count of 90.2 ± 4.03% in ewes, which in turn reduced pasture contamination. They also discovered that lambs born to vaccinated ewes had increased resistance to parasitic infections seeing a 37.1% reduction in their fecal egg counts by the time they were six weeks old (Teixeira et al., 2019).

For hair sheep, it is important to select parasitic resistance rather than resilience. Resilient animals are often heavily infested with parasites, contributing to increased pasture contamination by having higher fecal egg counts but presenting with minor or no parasite indicators such as reduced body condition or a poor FAMACHA© score. This can be potentially deadly to non-resilient sheep such as young lambs and gestating ewes (Barbosa-Toscano et al., 2019). There are breeds of sheep that have a higher rate of parasite resistance, such as the Red Maasai sheep native to Eastern Africa. On the other end of the spectrum, some breeds have a higher rate of susceptibility to parasites, including the Dorper sheep, native to Southern Africa (Bishop, 2012). These two breeds also represent how the environment can impact parasite resistance and susceptibility and why genetic selection for resistance is important. It is possible to breed better resistance into a flock and not allow the sheep to be exposed first (Bishop, 2015). Selecting for resistance ensures the animal has a lower parasite count, in turn lowering their fecal egg count. A lower egg count allows for less pasture contamination, allowing for less parasitic infection.

One of the most common non-parasitic diseases in both wooled and hair sheep is the inflammation of the mammary glands, known as mastitis. To check for this disease, veterinarians measure somatic cells, a higher cell count indicating infection in the glands. In sheep, the probability of developing mastitis has a genetic and environmental basis. Mastitis is considered the best disease to study in sheep when observing genetic resistance. Resistance to mastitis is a polygenic trait that can be inherited.

Footrot is the second most costly disease in hair sheep production. It is an often-contagious infectious disease caused by a variety of bacteria with the primary infecting bacterium being *Dichelobacter nodosus* (Raadsma and Egerton, 2013). Resistance for footrot is subgroup-specific, meaning an animal can have resistance to one subgroup of *D. nodosus*, but not another, making a genetic selection for resistance as well as non-genetic control factors increasingly difficult. Geneticists hypothesized that footrot resistance could be polygenetic but finding these genetic markers has proven to be difficult because of the disease variability (Bishop, 2015). Looking at nongenetic factors, age, and sex play important roles in footrot resistance. Rams are seen to be less resistant as compared to ewes and adults are less resistant than lambs (Raadsma and Egerton, 2013).

The high effectiveness of genetic selection to control a disease is seen in scrapie. This is a devastating neurological disease, classified as classical or nonclassical that initially was difficult to control in flocks. Then, genetic research was able to pinpoint polymorphisms on the PRNP gene at codons 136, 154, and 171 that code for the various scrapie haplotypes (Bishop, 2015). The PRNP gene also codes for the PrPC protein in certain breeds of sheep. This protein has multiple variants which determine resistance and susceptibility to scrapie. VRQ is the variant most directly linked to the susceptibility of classical scrapie while the ARR variant has been seen to cause resistance to classical scrapie (Hagenaars et al., 2018; Acín et al., 2021). Resistance to this disease is determined by genotype; VRQ homozygous animals are more at risk to develop scrapie while ARR heterozygous animals are seen to have a lower risk and being ARR homozygous results in total scrapie resistance. Careful selection to prevent these polymorphisms has led to an increase in scrapie resistance, especially in European countries, where rams discovered carrying the VRQ gene were castrated or culled from flocks (Acín et al., 2021).

3 Conclusions and prospects

Hair sheep when compared to wool sheep have advantages related to their management, easier to lamb, more prolific expressed as lambing per year, and higher survival of their lambs. Hair sheep also show more tolerance to heat stress than wool sheep but also can be affected by it.

Related to meat production, hair sheep have higher cholesterol levels in meat and lower yield. Hair sheep have also shown higher resistance to parasite infections as compared to wool animals. Having this many advantages, hair sheep are each time more popular and likely to be included in farm operations. However, more efficient, profitable, and sustainable production of hair sheep requires more in-depth studies through rigorous multidisciplinary research using systems science.

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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.

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