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Innovation systems for emerging food technologies: evidence from the development of cultured proteins in Thailand

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Introduction: Understanding how actors and institutions can support the adoption of novel technologies may help identify opportunities for stakeholders to accelerate transitions towards more sustainable production and consumption practices. Little is currently known about how emerging food technologies may be effectively supported in pre-market stages of development, especially in middle- and low-income countries with industrializing economies.

Methods: In this paper, we apply the theoretical framework of technological innovation systems to assess how actors, networks, and institutions are influencing the pre-market development of cultured protein (CP) technologies in Thailand. We used a mixed-methods approach that consisted of 1) a qualitative document review and 2) semi-structured interviews with 17 expert informants.

Results: We found that various actors have demonstrated preliminary engagement in the development of an innovation system for CP technologies in Thailand. However, technological diffusion will additionally require addressing a need for regulatory approval, manufacturing capacity, scientific and technical expertise, and consumer acceptance.

Discussion: Stronger evidence of the potential domestic benefits that CP production could bring to Thailand is a prerequisite for stakeholder engagement and mission alignment across sectors. In the near term, transnational coordination may be necessary to help overcome limitations in domestically available expertise. Our findings demonstrate the importance of a convergence in priorities for technological development and reveal a need for further research into how transnational linkages of innovation systems may help address national weaknesses by complementing resources and capabilities at the national level.

KEYWORDS

alternative proteins, alt-proteins, cultured proteins, cultivated proteins, protein, alt-meat, sustainability transitions, food technologies

1 Introduction

Significant changes to current food production and consumption practices are needed to achieve global climate change targets and ensure food security for a growing population (Ambikapathi et al., 2022; Clark et al., 2020). Technological innovation in the agri-food sector may help drive transitions toward more sustainable practices because technologies significantly influence the economic, environmental, and social dimensions of industrial development (Huang, 2021). In recent years, the use of fermentation technologies to create novel and potentially more sustainable food products has received increasing attention from researchers, investors, and entrepreneurs (Teng et al., 2021). Fermentation has been used for millennia to extend the shelf life of products, enhance their nutritional context, and improve yield. However, modern biotechnological advances have introduced opportunities to expand upon the use of fermentation technologies to produce novel food products in a more cost and resource efficient manner (Seo and Jin, 2022; Siddiqui et al., 2023; Teng et al., 2021). The application of fermentation to produce alternatives to products derived from animals has become a key area of new research in consideration of environmental and animal welfare concerns associated with conventional animal agriculture practices (Boukid et al., 2023; Smith et al., 2022). In contrast to approaches that aim to enhance the sustainability of traditional animal farming, such as agroecology (Dumont et al., 2013) or strategies to reduce enteric methane emissions from ruminants (Tseten et al., 2022), fermentation technologies could help mitigate the environmental impact of food systems by decreasing reliance on animal-derived products.

"Cultured proteins" (CP) (including cultured meat) are a class of food products, manufactured using advanced fermentation techniques, that serve as dietary substitutes to traditional animal-sourced foods. CP may also be referred to as "cultivated" proteins (Mittenzwei et al., 2025) or "cell-based foods" (FAO, 2023), and are often grouped together with plant-based substitutes for animal products (many of which have already been introduced in consumer markets globally) under the umbrella term "alternative protein" or "alt-protein" products (Onwezen et al., 2021). Yet, CP products are unique from alternative protein products made exclusively of plant-derived ingredients because they contain animal or fungi protein sources produced via fermentation processes (Smetana et al., 2023). CP can be (a) cellular products made of living or once living cells (e.g., cultured meat), (b) acellular products made of organic molecules (e.g., proteins and fats) that contain no cellular or living material in the final product (e.g., recombinant whey protein produced using precision fermentation), or (c) biomass products made of microorganisms with a high protein content (e.g., mycoprotein funghi-based products; GFI, 2021; New Harvest, n.d.). As compared to plant-based alternative protein products, CP products may appeal to a wider variety of consumers because they may be developed with sensory profiles more similar to animal-sourced foods (Souza Filho et al., 2019; Smith et al., 2022). Unlike plant-based food products, CP products remain in a novel stage of development and have not yet been widely introduced in global consumer markets.

CP technologies may be leveraged in the near future to help diversify the supply of protein-rich food products and reduce the consumption of animal-sourced foods (Singh et al., 2022; Smith et al., 2022). CP technologies require less land than conventional animal agriculture practices, tend to generate lower environmental impacts per unit of protein (e.g., eutrophication potential, acidification potential, and water use), and can have a lower carbon footprint particularly when produced with low-carbon energy sources (Santo et al., 2020; Siddiqui et al., 2023; Sinke et al., 2023). However, various constraints must be addressed to enable the cost-effective and efficient commercial-scale production of CP. For instance, numerous research and development challenges remain, especially in creating processes to effectively replicate the sensorial and nutritional characteristics of conventional meat products (Fraeye et al., 2020; Chriki et al., 2022). CP fermentation processes also tend to be energy intensive (Behm et al., 2022; Järviö et al., 2021; Mattick et al., 2015; Tuomisto and de Mattos, 2011; Tuomisto and Ryynänen, 2024), and some environmental impacts are highly dependent on production location, fermentation system design, and the inputs used in manufacturing (Tuomisto, 2022). Researchers are currently developing more energy efficient fermentation systems and pioneering the ability to utilize agri-waste sources, algae, and gasses as carbon sources in CP fermentation processes. If such advancements to improve the sustainability of CP production are commercialized (Banks et al., 2022; Lips, 2022; Ritala et al., 2017), CP technologies could help advance broader food system transformations to ensure access to safe, healthy, and affordable diets (Hadi and Brightwell, 2021).

In the past decade, research on alternative proteins has expanded beyond a primary focus on foundational technological research to include attention to factors that may inhibit or support consumer acceptance. More recently, alternative proteins have become an area of focus in sustainability transitions literature, a field concerned with how to promote and govern a fundamental transformation toward more sustainable modes of production and consumption (Aschemann-Witzel and Schulze, 2023; Markard et al., 2012; Vermunt et al., 2020). Researchers have advanced analytical frameworks for sustainability transitions previously developed through case studies in the energy and mobility sector by highlighting multiple conceptual factors related to successful technological diffusion in the agri-food sector (El Bilali, 2019; Köhler et al., 2019; Mylan et al., 2019). These factors include the importance of engagement from incumbent actors to support technological development and diffusion (Mylan et al., 2019), cognitive and normative legitimacy (Tziva et al., 2020; Bulah et al., 2023; Randelli and Rocchi, 2017), and international level knowledge transfer and consumer engagement as a trigger for the national development of sectors for new food products (Aschemann-Witzel and Schulze, 2023).

Most initial studies have concentrated on transitions in North American and European countries with well-established markets for alternative proteins (e.g., Aschemann-Witzel and Schulze, 2023; Mylan et al., 2019; Tziva et al., 2020; Schwarz et al., 2024). There remains a need for research to characterize the systems building processes between actors, institutions, and technologies that occur in the pre-market phase of the development for emerging food technologies, also known as the "formative stage of innovation system development" (Markard, 2020; Suurs et al., 2010). The formative stage of innovation system development includes the creation of networks and the design of institutions to make the technology fit better to its surrounding structures (Suurs et al., 2010). The formative stage of innovation system development is critical to shaping the potential for successful market diffusion. This stage may be particularly influential for the success of novel food technologies which depend on political and regulatory factors as well as consumer understanding and willingness to support (Stephens et al., 2018). In low-and middle-income countries where most economic growth is anticipated to occur between now and 2050 (Oates, 2021), the formative stage of innovation system development may manifest differently as compared to high income countries due to unique structural and cultural contexts that influence the way that actors, institutions, and technologies interact (Casadella and Tahi, 2022; Hansen et al., 2018).

In this paper, we ask the research question: *How might emerging innovation system dynamics influence the diffusion and adoption of novel food production technologies?* We select Thailand as a case study due to its potential to become a leading CP product manufacturer, supported by its strong food export reputation, abundant fermentation feedstocks, interest in agricultural modernization, and growing plant-based alt-protein market. We characterize how multisectoral stakeholder engagement has contributed to the formation of an innovation system for CP technologies in Thailand, drawing upon findings from a qualitative literature review. We assess factors hindering the mass commercialization of CP and opportunities for stakeholders to positively influence the development of CP innovation system in Thailand using data from interviews with key informants. We first highlight how actions taken by stakeholders have contributed to the development of an innovation system for CP technologies, then broaden our discussion to describe actionable opportunities for multisectoral stakeholder engagement to support the diffusion and adoption of CP technologies at a national and international scale. This paper addresses a need for research on innovation system dynamics for emerging systems (Suurs and Hekkert, 2009), and advances literature on the formation of agri-food innovation systems in low-and middle-income countries (Casadella and Tahi, 2022; Egbetokun et al., 2017; Siegrist and Hartmann, 2020). To the best of our knowledge, this paper is the first to assess resource needs to support the development of an innovation system for CP technologies. Unlike plant-based alternative protein products, CP products have not yet been widely diffused in consumer markets. Furthermore, by focusing our case study on Thailand, we help address a gap in the literature on alternative protein innovation system development in low- and middle-income countries with industrializing economies and rising rates of per-capita meat consumption. Through this approach, we develop novel insights into how emerging innovation system dynamics may support the future diffusion and adoption of nascent food technologies through investments, collaboration, and policymaking (Bulah et al., 2023).

2 Methods

2.1 Theoretical approach

The diffusion and adoption of new technologies is a complex reconfiguring process that depends on spatial and historical contexts as well as innovating actors and institutional structures. Before technologies reach the market, they are subjected to a formative stage of development, during which time they are modified by actors and institutions in networks of inter-organizational relationships (Jacobsson, 2004; Suurs and Hekkert, 2009). These actors, networks, and institutions compose an "innovation system" that contributes, positively or negatively, to the developing, diffusing, and utilizing of new products (Hayashi, 2020; Suurs and Hekkert, 2009). During the formative state of innovation system development, actors focus on research and development, experimentation, and prototyping. There are large uncertainties regarding which prototypes may gain traction, if there will be profitable applications, and whether there may be adequate consumer demand (Markard, 2020). The formative stage of development influences the diffusion and adoption of new technologies by shaping how existing innovation systems co-evolve and change as innovation systems emerge (Hekkert et al., 2007).

The concept of innovation systems was first developed at a national scale, but has since been extended to regional, sectoral, global, and technological levels (Hayashi, 2020). The concept of technological innovation systems (TIS) focuses on the development, diffusion, and use of a particular technology (Bergek et al., 2015; Musiolik and Markard, 2011). A TIS includes components dedicated to the specific technology and components that influence the innovation process for the technology (Bergek et al., 2015). In the context of CP technologies, multiple different sectors are implicated in the innovation process, spanning across public, private, and non-profit domains. In this research, we apply the framework of TIS to assess how actors, networks, and institutions are influencing the pre-market development of CP technologies in Thailand.

2.2 Case study

We focus on Thailand as a case study based on the country's key role as a food exporter in the Southeast Asia region and a few key indicators that the country could be well-equipped to manufacture CP. Thailand is one of the largest food exporting countries in the world and around one-third of the country's total workforce is employed in agriculture (The Thailand Board of Investment, 2018). However, the sector's relative contribution to national income has declined over the past three decades as the country has industrialized (Udomkerdmongkol, 2020), and is projected to face adverse effects due to climate change (Attavanich, 2013). The Thai national government is currently seeking opportunities to modernize its agricultural sector because of stagnating sectoral growth (Bangkok Post, 2020; Kosulwat, 2002; The World Bank, 2022).

Higher value agricultural and manufacturing applications such as CP could help support economic growth and increase the availability of domestic employment opportunities as the country continues to modernize (Bangkok Post, 2020). Thailand has a strong ecosystem for food manufacturing and a highly skilled food manufacturing labor force that could be engaged to support CP manufacturing efforts, especially given its abundant production of carbon-rich crops suitable for fermentation feedstocks (OECD, 2021). Thailand is often referred to as the "kitchen of the world" (The Thailand Board of Investment, 2018), and Thai food companies have a reputation for quality and reliability that could make them well-suited to become trusted producers of CP for export (Bangkok Post, 2021d). Additionally, as demand for animal-sourced foods continues to grow in the Southeast Asia region in association with rising incomes (Lee and Hansen, 2019), Thailand may face increasing pressure to produce for the animal-sourced foods supply chain. Diversification of protein-rich food production, including plant-based and CP protein products, may offer strategic advantages for food producers in Thailand.

Plant-based alt-protein products have become an export for Thailand (Royal Thai Embassy, 2022a), and CP products could be manufactured for similar export markets. Additionally, Thailand is located in close proximity to Singapore, a country that has introduced pioneering CP research and development (R&D) initiatives and approved the domestic retail of CP products (Bangkok Post, 2021c). Within Thailand, plant-based alt-protein products have become available, and the market for such products is expected to continue to grow in coming years (Rujivanarom, 2022; Royal Thai Embassy, 2022a). CP products could bolster consumer access to alt-protein products, especially if they are competitively priced and widely available in domestic retail markets. Taken together, these factors indicate that Thailand could be well-equipped to engage with, and benefit from, CP manufacturing.

2.3 Data collection

To explore how formative stage innovation system dynamics have affected and may continue to shape the diffusion and adoption of CP technologies in Thailand, we pursued a mixed-methods approach that consisted of (1) a qualitative document review and (2) semi-structured interviews with expert informants. This approach allowed us to contextualize the emergence of the CP innovation system within broader economic and historical contexts, and to collect qualitative data on the ways in which actors from multiple sectors are influencing the design and adjustment of technologies and institutions to support CP production (Forbes and Kirsch, 2011; Suurs and Hekkert, 2009). Further, our use of two sources of evidence enabled us to compare data across sources and reduce the impact of potential biases in relying on a single data source (Mackieson et al., 2019).

2.3.1 Qualitative document review

First, we searched for peer-reviewed literature using the academic databases Web of Science and Google Scholar to identify CP research and development efforts that have occurred in Thailand relevant to the development of a CP innovation system in Thailand (Rumrill et al., 2010), We screened for papers that included: (a) either a direct reference to "Thailand" or had an author affiliated with a Thai institution, and (b) a mention of "cultured protein" or a synonymous term (see the Supplementary material for further details). No papers met our inclusion criteria. As such, we concluded that there was an insufficient quantity of peer-reviewed research relevant to CP research and development in Thailand to inform an analysis of the state of Thailand's CP innovation system. While there may be a high quantity of research being produced by researchers in Thailand that could be leveraged to inform CP research and development, our findings indicate that there is not yet a significant body of published peer-reviewed research explicitly focused on CP technological development.

Second, we reviewed relevant media articles using the global news monitoring and search engine Factiva to identify (a) stakeholders engaged in Thailand's CP innovation system and (b) major developments reported on in global newspapers, newswires, industry publications, magazines, and reports. We used the search terms "Thailand" and "cultured protein" along with relevant synonyms (Supplementary material). Articles were included for screening if they were published in either Thai or English and discussed events relevant to the development of a CP innovation system that occurred in Thailand from January 1st, 2013 to May 16th, 2022. We selected 2013 due to its significance as the year that the first cultured meat prototype was publicized as a proof of CP's technological viability. Articles were screened and included for analysis if they contained explicit mention of an action or event relevant to the diffusion and adoption of CP technologies in Thailand. A total of 132 documents that met our inclusion criteria were included for data analysis.

2.3.2 Semi-structured interviews

To further identify relevant stakeholders and solicit insights into barriers and actionable opportunities that could further affect the diffusion and adoption of CP technologies in Thailand, we conducted semi-structured interviews with 17 expert informants. Interviews can help detect whether core actors perceive resource access to support technological knowledge production as a problem (Hekkert et al., 2007). The interpretative knowledge of experts that can be obtained through thematically structured interviews can be valuable due to their status and potential to meaningfully guide action (Bogner et al., 2009). We identified interviewees initially through our networks of colleagues and then through snowball sampling. Interviewees were invited to participate based on their self-identified knowledge relevant to Thailand and CP. Our sampling strategy targeted senior experts with explicit knowledge about the subject of CP in Thailand that were directly involved in decision-making processes that could influence CP diffusion or adoption. Interviewees included representatives of CP companies, Thai food companies, non-profit organizations, funding agencies, and governmental agencies.

Interviews were conducted in English, lasted between 30 and 82 min, and were recorded with the consent of the interviewees. In interviews with two interviewees from the same organizations, each interviewee was provided with the opportunity to share their own perspective on each question posed. Most interviews were conducted via Zoom, apart from three interviews conducted in-person in Thailand. We used a thematically organized semi-structured interview guide (Supplementary material), in which we asked our interviewees to comment on: (i) any recent changes or advancements in R&D, infrastructure development, investment, or attention in the cultured protein manufacturing sector in Thailand, (ii) protein technology type(s) that could gain the most traction in Thailand, (iii) novel opportunities for stakeholders engaged in the existing food, bio-pharmaceutical, and/or manufacturing sectors in Thailand, (iv) barriers to establishing CP manufacturing capacity in Thailand, and (v) actions that could or should be taken to maximize the opportunities and/or minimize the barriers identified by interviewees.

2.4 Data analysis

We analyzed the documents that met our inclusion criteria to identify relevant stakeholders and assess strategic actions that have been taken by actors and institutions during the formative stage of the development of a CP innovation system in Thailand. We extracted information on relevant policies, evidence of innovation system engagement from private or public sector stakeholders, and characteristics of Thailand's agricultural or manufacturing sector promoted by stakeholders as attributes that could support the diffusion and adoption of CP in Thailand. We also coded for barriers or opportunities referenced in the articles that could affect the adoption and diffusion of CP technologies. From each article, we extracted the year of publication, the media publication outlet, and the CP technology type(s) referenced (cellular agriculture, acellular agriculture, and biomass fermentation) from all articles. We coded data to categorize developments according to the type of action and the sector affliction of the actor promoting the action (See Supplementary Table S1 for the codebook used for the qualitative document analysis).

We coded all interview transcripts with MaxQDA software using a thematic analysis technique to identify existing barriers hindering the diffusion and adoption of CP, as well as opportunities for strategic action that could dynamically influence the shaping of a CP innovation system in Thailand (Kiger and Varpio, 2020). We coded for opportunities and barriers related to the establishment of a CP innovation system in Thailand, and categorized them based on their relevance to market, regulatory, investment, public sector support, social or cultural, scientific, or technical, and manufacturing fields. In addition, we noted relevant stakeholders mentioned by interviewees and identified key policies and characteristics of Thailand's agriculture or manufacturing sector that could be conducive to the growth of a CP innovation system, using codes derived from the literature review. We analyzed coded segments to inductively identify themes, and group coded segments according to theme. We reviewed and revised themes to ensure that each theme accurately represented a unique barrier or opportunity and possessed an adequate quantity of supporting data. We cite findings from interviews using the notation "(I*x*)," whereby *x* denotes the interview number.

3 Results

3.1 Multisectoral stakeholder engagement in the development of a cultured protein innovation system in Thailand

We found that private sector actors in Thailand are the primary stakeholders driving innovation system development in cultured protein (CP) technologies. Through our literature review, we identified numerous multinational food-producing companies based in Thailand that have expressed interest in expanding their line of alt-protein product offerings to include CP products (See Table 1). These companies, including Thai Union, CP Foods Global, BetaGro, Tyson and NR Instant Produce, have all either introduced their own product line of plant-based alternative protein products or partnered with CP start-ups to accelerate their scale-up and distribution (PRNewswire, 2021a; PRNewswire, 2021b; Thai Union, 2021). Interviewees confirmed this finding and suggested that the initiatives pursued by major Thai companies are indicative of their interest in becoming manufacturers of CP products (I1; I4; I7). As one interviewee remarked: "I think all of these [Thai companies] are realizing that is happening elsewhere in the world, that things are changing and that you need to join the party, or you may no longer be part of it…. products are being launched by Thai Union, by CP [Foods Global], by Tyson, everybody's jumping on the bandwagon" (I1). Notably, such initiatives have been pursued before a domestic consumer market for CP products has become well-established. Many interviewees emphasized the proactive nature of private sector initiatives to advance the manufacturing of alt-protein products, and in some cases expressed concern that Thai consumers may not be ready to adopt products introduced at a price premium (I1; I3; I4; I5; I12; I11).

Actors from the public sector and academia have partnered with major private sector companies leading the development of the CP innovation system in Thailand, demonstrating some interest in explicitly supporting developments that could accelerate the diffusion and adoption of CP technologies. For example, in 2019 the National Innovation Agency (a national government funding agency) established the "SPACE-F" accelerator and start-up incubator program to support early-stage CP companies in collaboration with the Thai Union Group and Mahidol University (SPACE-F, 2019). Some interviewees expressed the belief that national government stakeholders are "really starting to pay attention to the CP field," (I7) and increasingly willing to support CP research and development (I1; 15; 17; I11). An interviewee cited the convening of a roundtable discussion with stakeholders from multiple sectors to discuss the commercialization of CP technologies in Thailand as an example initiative taken by the public sector to support the advancement of a CP innovation system (I3).

Numerous recent actions by the national government to promote the growth of the agricultural sector have also resulted in policy changes conducive to the continued development of a CP innovation system in Thailand. For example, in 2021 the government endorsed a proposal to declare a Bio-Circular-Green ("BCG") economic model as part of the national agenda (Bangkok Post, 2020; NSTDA, 2022). The plan seeks to increase the value of farm products and generate more income for the agricultural sector, by promoting the use of advanced technologies and innovation in food-related industries (Bangkok Post, 2020; Bangkok Post, 2021b; NSTDA, 2022). Other incentives to support the advancement of the domestic bioeconomy include: a "smart visa" program to attract high-skilled professionals, investors, executives, and entrepreneurs; permission for non-Thai companies to own land in Thailand; grants for unlimited shareholding (i.e., the shares in a company that a particular person or organization owns) to non-Thai shareholders; and the construction of five "flagship corridors" to spread economic growth and new technologies to more regions of the country (Bangkok Post, 2020; Royal Thai Embassy, 2022b). The introduction of these national policies and initiatives

TABLE 1 Stakeholders (identified in our qualitative document review and/or interviews) engaged with the formative stage of the development of an innovation system for CP technologies in Thailand.

Private sector	Public sector	Civil society
Thai Union Group	National Government	Good Food Institute Asia Pacific
CP Foods Global	National Funding Agencies (e.g., the National Innovation Agency)	
BetaGro	The National Center for Genetic Engineering and Biotechnology (BIOTEC)	
NR Instant Produce		
Tyson	Thailand Bioresource Resource Center, the National Biobank of Thailand	
	Food Innopolis	
	Mahidol University	
	Chiang Mai University	
	Chulalongkorn University	
	King Mongkut's University of Technology Thonburi	
	Mae Fah Luang University	

reflect institutional shifts that could increase the likelihood of successful CP technological diffusion and adoption in Thailand.

Beyond these initiatives, the engagement of stakeholders from the public sector and civil society to establish an innovation system for CP technologies in Thailand has remained relatively limited. Many interviewees cited the "risk-averse" attitude of public sector stakeholders in Thailand and a hesitancy to support novel food and other high-tech innovation as a potential factor affecting their willingness to invest in CP research and development (I2; I3). As one interviewee stated: "There's a lot of commercial interest in trying to do things but there's no requisite kind of government support to help back that up or make it more widespread" (I3). Some interviewees referenced the lack of support from the national government as a factor hindering the engagement of academic researchers in the field, especially with respect to limited publicly funded research opportunities. Therefore, despite some recent examples of demonstrated interest from the government in supporting the development of Thailand's CP innovation system, interviewees tended to characterize the government's approach as "not very proactive" and "dependent on the corporates" for thought leadership (I3; I7). Additionally, aside from international non-profit CP advocacy groups such as the Good Food Institute Asia Pacific that include focus on Thailand as a key market (I9; GFI APAC, 2022), we did not find evidence of engagement from political lobbies or interest groups located in Thailand to support the diffusion and adoption of CP technologies.

3.2 Barriers to cultured protein diffusion and adoption in Thailand

Our interviews also revealed numerous barriers impeding the production of CP products in Thailand that could delay the adoption and diffusion of CP technologies. In the following subsections, we explore the nature of each barrier using data from our interviews.

3.2.1 Regulatory approval

Interviewees cited the lack of an appropriate regulatory framework in Thailand as the most immediate barrier that could prevent the commercialization of CP products and stall the establishment of a CP manufacturing sector (I3; I6; I9; I12; I13). CP biomass protein products that do not contain genetically engineered organisms or whole animal cells (e.g., products made from fungi or algae protein sources) may be more readily approved under Thailand's existing novel foods framework, but acellular and cellular CP products will likely require entirely new regulatory protocols. Although it could be feasible for Thailand to produce CP products for export markets without domestic regulatory approval, many stakeholders emphasized that it may be critical or highly advantageous for Thailand to develop a regulatory framework for the domestic retail of CP products (I1; I13).

Interviewees reported some progress on the development of a regulatory framework for CP products. They indicated that some initial conversations have been facilitated by the Thai Food and Drug Administration (FDA) to solicit the expertise of stakeholders within public research funding organizations and the private sector (I4; I5). However, there was no consensus among interviewees regarding when a regulatory framework would be introduced. Many interviewees characterized existing regulatory processes as "slow" and "unclear," and additionally expressed concern that the Thai FDA may not have the in-house expertise to inform the development of a regulatory framework for CP products (I1; I3; I5; I8). Some interviewees expressed the concern that the growth of Thailand's CP sector could be hindered if the passing of regulation lags significantly behind innovation (I9; I3; I13). The establishment of a regulatory framework for CP products may therefore significantly influence the pace at which CP technologies are diffused and adopted in Thailand.

3.2.2 Manufacturing capacity

Producing CP for consumer markets requires physical manufacturing infrastructure suitable for commercial-scale CP production. Multiple interviewees commented that CP producers could be drawn to Thailand as a manufacturing destination in consideration of the country's geographic proximity to other countries, reputation as a food exporter, land availability, and advantageous manufacturing costs (I1; I2; I3; I6; I10; I11; I12). Thailand produces a wealth of carbon-rich crops such as sugarcane and cassava, which have historically been used as feedstocks in fermentation processes to produce non-food or animal feed products (e.g., biofuels, biopharmaceuticals, liquid feed enzymes) (Ngammuangtueng et al., 2020). Existing manufacturing sites from these adjacent fermentation industries or the food and beverage manufacturing industry might be suitable for CP production if retrofitted accordingly (I2). However, there is currently little systematic information about the location, scale, and availability of existing fermentation manufacturing sites (I12).

Interviewees anticipated it could be difficult to identify investors willing to finance the construction of intermediate-and commercial-scale CP manufacturing sites (I4; I10). Constructing new commercial-scale fermentation manufacturing sites or retrofitting existing ones may come at a significant expense with long investment return timelines (I4). They noted that funding from angel investors and the public funding agencies has been sufficient to support initial CP research and development efforts in Thailand, but currently "is not large enough to take the lead… for the growth stage" (I10). For example, researchers at Chulalongkorn University have successfully developed cultured pork product prototypes but have not yet scaled production beyond the lab bench scale (I4; I6; I9; Prachachat, 2021). An opportunity to substantially reduce the cost of establishing novel production manufacturing sites and the need for capital-intensive investments could be to develop CP manufacturing protocols that utilize food-grade rather than pharmaceutical-grade fermentation infrastructure. As one interviewee remarked: "if someone starts figuring out how to produce the meat by using food grade equipment, that'll be fantastic and cut the costs in half." (I1) Innovative research and development efforts to reduce the cost of CP fermentation bioprocess design could therefore help overcome the need for significant investments to support commercial-scale CP production.

3.2.3 Scientific and technical expertise

Thailand currently lacks opportunities for researchers to engage with educational and experiential learning opportunities directly relevant to CP production. Interviewees noted that biotechnological research for food applications is not a key focus at many domestic universities, and there are few opportunities to pursue CP research at such institutions (I2; I3; I6; I11; I12). Publicly funded CP research efforts in Thailand were described as "scattered and siloed," and interviewees noted that the perception of public funding for CP research as unreliable could be limiting researcher engagement in the field (I5; I3). Some interviewees expressed concern that companies may be deterred from establishing a CP manufacturing base in Thailand because the country does not currently have enough people with food technology expertise in select fields critical to scaling CP manufacturing such as tissue engineering, bioprocess engineering, and bioreactor design (I2; I6; I7; I12; I13). This aligns with findings from our literature review suggesting that only 30% of Thai graduates are from science, technology, engineering, art, and mathematics fields (Bangkok Post, 2021a). To compensate for this lack of trained expert labor, in the near-term it may be necessary to recruit individuals with expertise in such fields from abroad, to support CP companies translating their production protocols to commercial-scale levels of production (I6; I10).

3.2.4 Market size

Interviewees generally viewed the domestic market for CP products as limited and potentially inadequate to sustain the continued growth of a CP innovation system in Thailand. Price and taste were identified as the primary factors motivating consumer food purchasing decisions in Thailand (I3; I6), with high prices frequently cited as a barrier to potential consumer acceptance for CP products (I1; I3; I4; I10; I11). Consumer attachment to meat-eating practices and the high affordability and accessibility of animal sourced foods were also considered significant barriers to CP adoption (I1; I12), Since food in Thailand is typically inexpensive and easily accessible, consumers may lack the motivation to go out of their way to purchase CP products, especially if priced at a premium. Further, sustainability concerns were widely perceived as being insufficient to motivate consumers to change their consumption patterns (I1; I3); as one interviewee remarked: "people are not gonna go shop in droves for more sustainable solutions just for the sake of it." (I1) A lack of consumer education was also mentioned as a key factor limiting the market size for CP products (I4; I6; I7). Interviewees discussed the possibility that CP products could be seen as a fad due to limited awareness of both CP technologies and the potential benefits that CP production could offer to producers and consumers in Thailand (I2; I3; I6;12).

3.3 Opportunities for different stakeholders to help accelerate cultured protein diffusion and adoption in Thailand

This section describes opportunities, identified by interviewees, for various stakeholders to help accelerate the adoption and diffusion of CP technologies in Thailand. We present these opportunities according to the primary stakeholder type ideally positioned to advance each opportunity (Figure 1).

3.3.1 Public sector

3.3.1.1 Regulatory agencies

Several interviewees suggested that regulatory approval for manufacturing CP products in Thailand could be accelerated by adopting novel food frameworks from countries with expertise in CP

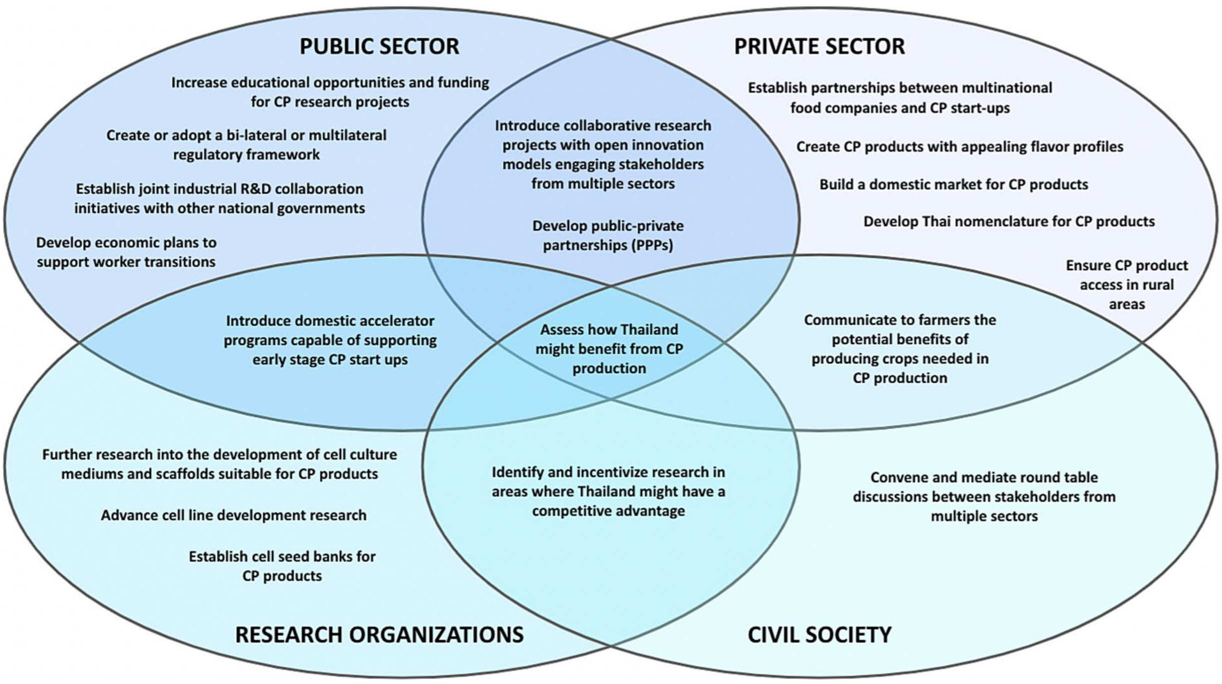

FIGURE 1
Opportunities identified by interviewees for different stakeholders to help accelerate cultured protein diffusion and adoption in Thailand. Example opportunities for cross-sector collaboration are included in the overlapping circles.

technologies. This could also involve the creation of bilateral or multilateral regulatory frameworks in collaboration with other nations, or the approval of regulatory frameworks that could be developed by international food regulations bodies in the near future (I9; I12). Some interviewees expressed an expectation that the Thai FDA could be open to accepting an externally developed reputable regulatory framework for CP products (I5; I9; I1; 13).

3.3.1.2 Other public sector stakeholders

Public research funding could be an avenue to increase the pool of researchers equipped with the expertise to contribute to CP research and development efforts (I3; I5). Increasing educational opportunities and funding for CP research projects at universities and national research centers well-equipped to support technology transfer between stakeholders in the private and public sectors (e.g., BIOTEC) could be especially impactful (I2l I6; I9). Additionally, interviewees referenced the introduction of collaborative research projects with open innovation models that engage stakeholders from multiple sectors as an opportunity that could help accelerate the advancement of CP research (I3; I4; I8).

Engagement from the public sector to determine Thailand's potential strengths as a producer of CP could also influence the trajectory of CP diffusion and adoption. Interviewees from multiple sectors emphasized the pressing need for the engagement of Thai civil servants to comprehensively assess how Thailand could best contribute to advancing CP production (I3; I2; I7; I12). As one interviewee pointed out: "it really depends on how Thailand wants to tackle this problem, right? Do you want to be the IP owners, or do you want to be the manufacturing hub for these products? Because the chosen strategy would then affect what they choose to do." (I13) Over-reliance on the private sector to develop CP products may also detract from the benefits that Thai people could experience through the growth of a domestic CP innovation system. As one interviewee described, what might be most profitable or preferable for one or more private companies may not align with (and could even detract from) the benefits that Thai producers and consumers could experience through alternative approaches to the adoption and diffusion of CP technologies (I7).

Interviewees identified multiple other opportunities that could be pursued by the public sector to support the development of a CP innovation system in Thailand. First, the government could introduce domestic accelerator programs capable of supporting early-stage CP startups. "Space-F" is currently the only Thai accelerator program with the resources to support CP startups. Introducing additional domestic accelerator programs could help attract individuals with relevant talent and expertise to Thailand (I6; I3). Second, developing public-private partnerships (PPPs) to support the development of the CP innovation system in Thailand could help demonstrate to the government that the sector can generate new employment opportunities while furthering efforts to achieve sustainable food production ambitions (I12). Third, joint industrial R&D collaboration initiatives between the Thai government and other national governments could help incentivize CP companies to locate R&D and scale-up efforts in Thailand and advance the competitiveness of the domestic CP innovation system. One example of such an initiative is the Singapore-Israel Industrial Research and Development Foundation (SIIRD), which funds early-stage startups to develop novel commercializable products in collaboration with partners located in both Singapore and Israel (I13). Additionally, Memorandums of Understanding (MOUs) could facilitate the sharing of knowledge relevant to CP regulation between Thai government agencies and other countries (I12). Finally, the government could develop economic plans to support workers in Thailand who are currently engaged in animal agriculture to transition toward alternative livelihood opportunities that could emerge through the development of the domestic CP innovation system (I12).

3.3.2 Private sector

3.3.2.1 Thai food-producing companies

Many interviewees expressed that the Thai multinational food companies that have led the development of the CP innovation system in Thailand could be best positioned to drive its continued expansion (I1; I3; I5; I6; I9). Although internal CP research and development efforts within these companies remain limited, they may be poised to contribute to the adoption and diffusion of CP technologies in Thailand once production protocols have been developed (I5; I6; 17; 19). Partnerships between Thai multinational food companies and start-ups with alt-protein expertise could help companies overcome their lack of specialized knowledge in-house by "leapfrog[ing] the development phase." (I3) As one interviewee remarked, multinational food companies are already engaged with food production, and therefore "know how to run a factory or the real manufacturing plants for animal products" (I6). These companies also have experience formulating products and may be particularly effective in leveraging their expertise to make products with appealing flavor profiles. One interviewee commented: "From what I can see the most potential is the final stage where you already have cells, you already have everything, the technology, and protocols, and you need the product formation. I think that will be something that the food producers here in Thailand are quite good at and they can add in creativity… We've always claimed that Thailand is the kitchen of the world…. [and] in the product formulations, we have really good scientists that can help generate new formulas or new types of products." (I6).

3.3.2.2 Other private sector companies

Interviewees stressed the need for support from other private sector companies, especially from industries such as marketing, advertising and sales, food service, and food retail, to help build a market for CP products in Thailand and foster consumer acceptance for CP products (I2; I4). Nomenclature for CP products has not yet been fully developed in Thai, and the terminology used to describe CP products could have a significant influence on consumer willingness to incorporate CP products into their diets (I4). Some interviewees perceived the relative "openness" of Thai consumers to trying new food products as a potential opportunity to drive domestic consumer adoption of CP products (I1;13). A survey conducted by Thai Union and Aleph Farms similarly found that 97% of Thai consumers may be willing to try cultured meat products (PRNewswire, 2021a). However, as one interviewee stated, "the challenge will be whether [Thai consumers] are going to stick to it." (I3) The affordability of CP products was unanimously cited as a factor that could have a critical influence on sustained consumer demand (I1; I3; I4; I5; I12). Alt-protein products in Thailand are currently more widely accessible in urban settings and ensuring access to CP products in rural areas

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may require further engagement of food service providers and retailers as the industry develops (I12).

3.3.3 Research organizations

Our interviewees cited several topics on which research organizations in Thailand might have expertise that could be applied to advance CP related research. Multiple interviewees concurred that research on cell line development and establishing cell seed banks could be areas where Thailand could become a leader (I5; I7; I11; I12). They cited access to reefs, fisheries, and poultry farms in Thailand as potential resources that could help support such research (I1; I6; I7). For example, existing research on black tiger shrimp could be applied to help inform CP cell line development (I6). The country's high number of researchers with specializations in molecular biology and edible nanomaterial development was also mentioned as an opportunity to contribute to the development of cell culture mediums and scaffolds suitable for CP products (I5). Finally, interviewees identified numerous research centers and universities with resources and expertise that could be leveraged to advance CP research. These institutions include: The National Center for Genetic Engineering and Biotechnology (BIOTEC), Thailand Bioresource Resource Center, the National Biobank of Thailand, Food Innopolis, Chiang Mai University, Chulalongkorn University, King Mongkut's University of Technology Thonburi, and Mae Fah Luang University (Table 1).

3.3.4 Civil society

Members of civil society, particularly non-profit and advocacy organizations, could play an important role in building stakeholder support for the development of a CP innovation system in Thailand by highlighting the country's unique advantages as a potential CP producer. These potential benefits could relate to characteristics that could attract CP companies and investors to Thailand as a manufacturing destination, including the country's access to natural resources, advantageous operating costs, or the availability of agricultural and manufacturing labor (I2; I3). Stakeholders who have experience working with farmers could also help communicate to farmers the potential economic and environmental benefits of transitioning to the production of crops needed in CP production (I3; I12). To advance academic interest in the field, civil society could also help identify and incentivize research in areas in which Thailand might have a competitive advantage (I7). Interviewees also expressed the need for a neutral stakeholder from civil society to convene and mediate round table discussions between stakeholders from multiple sectors to initiate the development of a plan to accelerate the diffusion of CP technologies in Thailand (I3; I12).

4 Discussion

4.1 Summary of results

We found that stakeholders in the private sector have been leading the formative stage of the development of a cultured protein (CP) innovation system in Thailand. Established multinational food producing companies have diversified their business strategies to invest in cultured protein (CP) technologies. Providing a structural foundation for the emergence of a CP industry in Thailand. In contrast, public sector and civil society stakeholders have been cautious to explicitly support the development of a CP innovation system, though they have expressed interest in conducting research that could advance CP R&D efforts. Our interviewees highlighted a multitude of barriers related to regulation, manufacturing capacity, CP product affordability, and consumer acceptance that would need to be overcome for the CP innovation system in Thailand to progress from a formative to a growth phase. Determining Thailand's potential strengths as a producer of CP and the benefits that Thailand may reap from CP production could help motivate increased stakeholder engagement and mission alignment to tackle priorities in CP development, including the barriers we identified. The formative stage of the development of new technologies lasts an average of about two decades (Bento and Wilson, 2016). Overcoming the challenges of the formative stage and advancing to the scaling and diffusing CP technologies will require the active engagement of multiple stakeholder types.

4.2 Scaling the development of a CP innovation system in Thailand

Many of the barriers to establishing a CP innovation system in Thailand identified through our research have also been identified in research on the diffusion and adoption of alt-protein technologies at a global scale. These include uncertainties in regulatory approval processes (Stephens et al., 2018), shortages in the availability of manufacturing equipment for commercial-scale CP production (Colgrave et al., 2021) high product prices (Tso et al., 2021), and limited consumer acceptance and familiarity (Bryant and Barnett, 2020; Onwezen et al., 2021). A more limited body of CP research has also called attention to the role that non-profit organizations could play in convening a diversity of stakeholders to accelerate the adoption and diffusion of CP technologies (Chiles et al., 2021; Newton and Blaustein-Rejto, 2021). Interestingly, while many of our interviewees mentioned the need for technical expertise and knowledge transfer to support CP diffusion and adoption, little research has explicitly explored human capital as a potential obstacle to CP diffusion. This may be due to the nascent nature of the CP industry and a knowledge gap concerning the specific forms of human capital that might be required to support the day-to-day operations of commercial scale manufacturing plants.

Our study on CP technologies provides valuable insights into factors affecting innovation system development in the food sector. One key factor is the need for regulatory approval processes to ensure the safety of products manufactured with new technologies is particularly relevant to the food sector. More broadly, food consumption patterns and dietary practices are influenced by a diversity of sociocultural influences, and consumer demand plays a critical role in driving sustainability transitions that involve novel foods (Monterrosa et al., 2020). Our findings align with previous literature suggesting that cognitive and normative institutions (i.e., values, beliefs, and associations) are especially pertinent to consider in research and policy making efforts to drive sustainability transitions involving alt-protein technologies (Bulah et al., 2023; Tziva et al., 2020). For example, mental associations elicited by different terminology influence consumers' associations, attitudes, and behavioral intentions toward CP products (Malerich and Bryant, 2022; Bryant and Barnett, 2019). Interviewees noted that there has not yet emerged a consensus regarding the most accurate and appropriate terminology to regulate the labeling of CP products in English or Thai. They mentioned the development of Thai nomenclature to describe and regulate CP products that elicit positive associations as a key opportunity to heighten consumer appeal. Interviewees also referenced Thailand's cultural openness to trying foods that are not widely consumed in other countries (e.g., insects) as a factor that could favor consumer interest in adopting CP products into their diets (Nimacimu and Su, 2024). Research on Thai consumer intent to consume CP products remains limited. However, a recent study assessing intent to consume various alt-protein types within a multi-ethnic Asian population found a relatively similar willingness to consume plant-based meat alternatives as compared to cultured meat products (29 and 25% of surveyed respondents, respectively) (Chia et al., 2024).

Our findings reinforce the notion that coordination among actors to formulate clear, timebound, and ambitious goals may be especially critical in sustainability transitions that involve tackling societal challenges (Elzinga et al., 2023). Notably, the manufacture of CP products could offer many benefits, including to improve animal welfare, support progress toward several UN Sustainable Development Goals, reduce the spread of disease, and improve food security (Holmes et al., 2022). However, the fulfillment of these mission-oriented objectives is by no means guaranteed; they may only be achieved if they are actively prioritized in the course of CP technological development (Holmes et al., 2022). Our findings suggest that the CP innovation system in Thailand will likely require a long formative stage due to the requisite knowledge, institutional capacity, and infrastructure to mature and scale up CP technologies (Bento and Wilson, 2016). To realize the full societal benefits of CP technologies, strong stakeholder alignment and collaboration will be essential to develop and promote mutually agreed upon solutions. Therefore, designing and producing CP in a manner that facilitates consumer acceptance and delivers on mission-oriented objectives may be time-consuming, and could conflict with some stakeholders' ambitions to bring CP products rapidly to market.

Our results also highlight the importance of institutional alignment and timely strategic action to encourage technological adoption. Institutional alignment can support a systemic and sustained approach to technology development as well as the generation of markets for new technologies through the formation of market regulations, tax policies, and value systems (Bento and Wilson, 2016; Jacobsson, 2004). Multiple interviewees remarked on the need for greater directionality and alignment in the mission for CP technological development in Thailand to promote multi-sectoral stakeholder engagement. In particular, they emphasized the need to determine Thailand's strengths as a CP producer and how stakeholders in Thailand may benefit from CP production. Collaboration and alignment in stakeholder priorities could help overcome barriers in policy development, including ensuring that regulation does not lag too far behind CP research and development efforts. Furthermore, constructing physical infrastructure for manufacturing CP products at a commercial scale could require significant investment, and it remains unclear where such funding could come from. Institutional alignment could help overcome such barriers to identify foci for research and investment and allocate financial and human capital to support CP commercialization (Hekkert et al., 2007). For example, prioritizing the development of more cost and resource efficient fermentation bioprocess designs for commercial-scale CP manufacturing could help address a significant technological development need.

Interviewees' emphasis on the need to assess how stakeholders in Thailand may benefit from CP production underscores the importance of considering how distinct political and social contexts may shape technological innovation system development in low- and middle-income countries. Much of the existing literature on the adoption and diffusion of alternative proteins has focused on North American and European countries where markets for alternative proteins tend to be more well-established, multi-sectoral collaborations to support alternative protein development are common, and meat substitute firms have been active for decades (Morris et al., 2021; Sexton et al., 2022; Tziva et al., 2020; Weinrich, 2018). For example, the Netherlands has established innovation clusters involving alternative protein firms and leading Dutch universities (Tziva et al., 2020), and the government has a "National Protein Strategy" focused on increasing domestic production of new protein-rich foods in a sustainable way (Ministerie van Landbouw, 2020). In general, high-income countries tend to have stagnating or declining meat consumption (Vranken et al., 2014) and public sectors supporting transitions toward diets less dependent on animal source foods (Steenson and Buttriss, 2021). These countries may also have diverse strategic interests that motivate their investments into building capacity to produce alt-proteins, such as reducing their reliance on food imports and boosting domestic food security (Staff and Wrobel, 2024; EDB Singapore, 2022).

In contrast to high-income countries where most research on the diffusion and adoption of alternative proteins has been concentrated, Thailand and other low-and middle-income countries may lack public sector support for reduced meat consumption. They may also have different national priorities that influence their motivation (or lack thereof) to invest in CP, and distinct political and cultural circumstances that affect barriers and opportunities to support CP diffusion and adoption (Liu et al., 2021). In our research, interviewees contextualized public sector hesitancy to invest in the upscaling of CP production as part of the Thai government's more conservative approach to supporting novel innovations. This limited public sector engagement could interact with other barriers to CP diffusion and adoption, such as low public awareness of CP products and potential limitations in market size. However, greater public sector engagement could be motivated by further proof of the socio-economic viability of the CP sector in Thailand, as well as by increased consumer interest in reducing animal source foods consumption. Considering that the potential socio-economic impacts of the CP industry remain uncertain (Morais-da-Silva et al., 2022a) and there continues to be disagreement regarding the extent to which alternative proteins may be disruptive to existing industries (Guthman and Biltekoff, 2021; Siegrist and Hartmann, 2023), this finding reinforces the notion that the development of a CP innovation system in Thailand will require further proof of socio-economic benefits. More broadly, this finding emphasizes the need for considering how the diverse political, socio-economic, and cultural considerations that characterize countries outside of Europe and North America may shape technological innovation system dynamics and development.

Our finding that the private sector has been leading the development of a CP innovation system in Thailand illustrates how a global decline in the share of public expenditure in agricultural GDP from 1980 to 2000 has left the development of more sustainable food products primarily in the hands of private sector stakeholders (Fuglie, 2016; Suphannachart, 2019; Zurek et al., 2021; The World Bank and the UK Department for International Development, 2011). Private sector actors often prioritize for-profit aims over the common good (Zurek et al., 2022), and some interviewees expressed concern that private sector stakeholders may not be best positioned to maximize benefits for Thai society from development of a CP innovation system. Interviewees highlighted the need for a neutral stakeholder to convene actors from multiple sectors and to clearly demonstrate the economic and non-economic benefits that the CP manufacturing could bring to Thai people and the national economy. This finding aligns with an emphasis in sustainability transitions literature on the role of coalition building to encourage technological adoption. Emerging technologies may benefit from the support of advocates from "technology specific coalitions," or political networks that have the objective of inducing institutional changes for new technologies to gain traction (Jacobsson, 2004). Technology-specific coalitions can build support among broader advocacy coalitions, which have the strength to shape policy agendas, influence institutions, and secure institutional alignment (Gabehart et al., 2022; Hess, 2019). Our findings indicate that such coalition building efforts may be crucial in promoting the public good in the diffusion and adoption of CP technologies in Thailand.

Finally, our findings suggest that collaboration between countries, especially between those with different competencies or expertise, may help expedite the development of a CP innovation system in Thailand and address limitations in domestic expertise and manufacturing capabilities. Cross-border, transnational linkages of innovation systems may help address national weaknesses by compensating for resources and capabilities missing at the national level (Wieczorek et al., 2015). For example, the adoption of a bilateral, multilateral, or international regulatory framework for CP products was cited by interviewees as an opportunity that could circumvent the need for the Thai FDA to design its own regulatory approval processes and fast track consumer access to CP products in Thai markets. The Codex Alimentarius Commission (established by the Food and Agriculture Organization of the United Nations and the World Health Organization) may be particularly well-positioned to introduce an international regulatory framework for CP products, which could further help facilitate global trade of CP products. Additionally, interviewees suggested it may be necessary to recruit individuals from abroad to compensate for shortages in domestic technical expertise relevant to CP, at least in the near term before more CP research and manufacturing training opportunities are established in Thailand. Notably, previous research on the establishment of innovation systems has largely focused on national innovation systems as a unit of analysis in part due to policymakers' capacity to shape institutions to meet national interests (López-Rubio et al., 2022; Anadon et al., 2016). However, our results suggest that increased global coordination and collaboration could be critical to driving CP diffusion and adoption in Thailand.

4.3 Caveats and limitations

Our results are based in part on the informed insights of expert stakeholders about the opportunities and barriers that could further accelerate or impede the diffusion and adoption of CP technologies in Thailand. Some of these insights are necessarily speculative. The development of a CP innovation system in Thailand remains in a formative stage of development and, as previously mentioned, this research does not attempt to assess the likelihood that the CP innovation system will continue to mature. Some barriers and opportunities were mentioned by more interviewees than others, as we note in the results, but our analysis did not attempt to assess the relative importance of any opportunity or barrier vis-a-vis another. Finally, our document analysis of key advancements in the development of a CP innovation system in Thailand only included documents published from 2013 to 2022, and only those from national or international media outlets. We did not have access to publications from local media outlets in Thailand. As a result, our findings may have failed to consider key developments, opportunities, or barriers that have occurred more recently or that were reported only at sub-national scales.

4.4 Future research opportunities

This research generates important insights into how multisectoral stakeholder engagement could affect the adoption and diffusion of new food technologies. Most research on sustainability transitions toward novel food technologies has been conducted in Europe and North America, and our emphasis on Thailand as a case study for national-scale analysis helps fill a critical research gap in non-high income countries (Casadella and Tahi, 2022; Egbetokun et al., 2017; Siegrist and Hartmann, 2020). Our findings emphasize that the distinct political and cultural contexts that characterize low- and middle-income countries may influence barriers and opportunities for CP diffusion and adoption. These factors vary dramatically across geographies and require further consideration in future research. As CP technologies are introduced globally, it would also be useful to examine how intergovernmental policymaking can trigger national-level developments (Aschemann-Witzel and Schulze, 2023; Fuenfschilling and Binz, 2018). For example, the introduction of an international regulatory framework for CP products by The Codex Alimentarius Commission could significantly affect food trade patterns and the pace of CP diffusion and adoption in multiple countries.

Additionally, while research has identified the need for both public and private sector engagement to enact food system transitions (Zurek et al., 2022), the mutual interdependencies and potential responsibilities of actors and institutions from different sectors in enacting food system transitions remains under explored. Our research highlights some opportunities for cross-sector initiatives, such as the development of private-public partnerships and open innovation research models. However, further research is needed to assess how such collaborative cross-sectoral initiatives or multi-actor governance models can be oriented to promote the common good in food technology transitions. In particular, it is unclear what conditions are capable of stimulating sustained collective action between actors from multiple sectors to enact sustainability transitions through the transformation of institutional arrangements (Jolly et al., 2016). Creating an enabling environment for such transitions may require the development of incentives that motivate multi-sectoral engagement and foster long-term cooperation and knowledge exchange (Brouwer et al., 2020). Minimizing job disruption and maximizing knowledge continuity could have positive implications for jobs and value creation, thereby increasing the political feasibility of a transition toward new food production technologies (Andersen et al., 2020; Morais-da-Silva et al., 2022b; Newton and Blaustein-Rejto, 2021).

Furthermore, we found that transnational coordination could be critical to accelerating CP diffusion and adoption, yet there are currently few models of transnational institutions capable of driving technological innovation for sustainable development (Anadon et al., 2016). There is a need for further research into potential global governance arrangements that could help drive sustainability transitions to make novel food technologies accessible to all populations. Thailand provides a relevant example in the field of global health, where the government has created an international collaborative network involving multiple government departments and global institutions. This network is responsible for governing international trade and health, aiming to strengthen institutional capacities and generate evidence-based policy decisions to improve health outcomes for the Thai population. This approach has successfully fostered a greater coherence between trade and global health, and may serve as a model that could similarly be applied to the governance and trade of novel food technologies (Friel et al., 2020; ITH, 2019; Thaiprayoon and Smith, 2015). Such global governance arrangements could also adopt inclusive development models that prioritize broad and diverse stakeholder engagement to ensure that the costs of transitioning to new food production systems are not disproportionately borne by specific groups (Brouwer et al., 2020; Zurek et al., 2021). Tools such as foresight methods or food justice frameworks could be applied to analyze potential trade-offs between food and nutritional security objectives and to elucidate additional goals for food system management (e.g., environmental sustainability, livelihood opportunities, and equity considerations) (Broad and Chiles, 2022; Zurek et al., 2021). These insights could inform the development of governance mechanisms designed to promote more just food system outcomes in the global introduction of novel food technologies such as CP.

5 Conclusion

Our research characterizes how the strategic actions of actors and institutions from multiple sectors have shaped the development of a cultured protein (CP) technological innovation system in Thailand. To date, the formative stage of the development of a CP innovation system in Thailand has been led by private sector actors, with some engagement from public funding agencies, academia, and research institutes. Key barriers that currently impede technological diffusion include uncertainties in regulatory approval processes for CP products, limited publicly funded research opportunities, and an absence of national and sub-national advocacy groups dedicated to coalition building to encourage technological adoption. Increased human and manufacturing capital, institutional alignment, and timely strategic action may help overcome these barriers to CP diffusion and adoption. Our findings also highlight several opportunities that could accelerate the adoption and diffusion of CP technologies in Thailand, considering the country's national context. These opportunities include demonstrating the potential socio-economic benefits of the CP sector, forming technology-specific coalitions to support the advancement of CP technologies, and fostering international collaborations between countries with different competencies or expertise. Our findings provide insights into how globally relevant barriers to the adoption of novel food technologies can impact the development of technological innovation systems at the national level. These findings can inform decision-making in Thailand and other countries as they seek to advance food system transformations, including through the development of cultured proteins and other new food technologies.

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.

Ethics statement

The studies involving humans were approved by University of Colorado Boulder Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

WE: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. DB-R: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. SS: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. AS: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. PN: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

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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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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1497792/full#supplementary-material

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