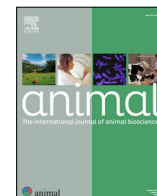




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Review – Insect farming for food and feed in the Global South: Focus on black soldier fly production [☆]

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ABSTRACT

Clear differences exist between the Global South and the Global North with respect to economic development. The majority of small and medium-sized insect production farms are located in Africa, Asia, and Latin America, which face challenges to food production and organic waste management in general. These regions have a long history of insect use, as well as environmental advantages, making production of insects in general – and the black soldier fly in particular – a promising option for sustainable food production and organic waste management. This study aimed to identify the current state of black soldier fly (*Hermetia illucens* L.) production in the Global South. The results of a survey and a Strengths, Weaknesses, Opportunities, and Threats Analysis are presented; responses were obtained from 33 of the 100 insect producers contacted: 14 in Africa, 4 in Latin America, and 15 in Asia. Their responses indicate that although insects have great potential and can help meet many of the Sustainable development goals thanks to their ecosystem services they provide – which is one of the main reasons producers engage in their production, significant challenges exist to the sustainability of insect farming, including lack of an adequate regulatory framework, an unstable supply of raw materials, market instability, and lack of adequate technology for operational scaling. Global collaboration among all stakeholders is crucial to overcoming these challenges.

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Implications

This study explores the current state of black soldier fly farming in the Global South, focusing on its potential for sustainable food production and organic waste management. By analyzing responses from black soldier fly producers in Africa, Asia, and Latin America, the research highlights both the opportunities and challenges faced by this emerging industry. The findings underscore the importance of black soldier fly farming in achieving food security, reducing waste, and promoting economic development in these regions. This work is a significant contribution to animal research, providing valuable insights for policymakers, researchers, and industry stakeholders in this emerging field of animal production.

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Introduction

Broadly speaking, two economic worlds exist: the Global North and the Global South. The Global North consists of societies in Europe, North America, Australia, Japan, and other regions conventionally perceived as being economically “advanced”, while the Global South consists of those societies – principally in Africa, Asia, and Latin America – which have not shared the economic benefits of the Global North (Odeh, 2010). Over 65% of the world’s small- and medium-scale farms are in the Global South (Todaro and Smith, 2020), where 58% of the labor force engages in agriculture, producing 14% of the gross national income. According to Mwangi and Kariuki (2015), residents of the Global South farm use low levels of technological development because their low incomes do not allow for investing in infrastructure and equipment. Small- and medium-scale farmers of Latin America, Asia, and Africa face a similar set of challenges related to social issues, governance, and equity (Dupont et al., 2018). On a global level, more than 80% of those living in extreme poverty live in rural areas, and rural pov-

erty rates are nearly three times as high as those of urban areas (United Nations, 2020). This disparity is expected to persist, largely due to ongoing challenges such as slow recovery from the COVID-19 pandemic, political conflicts, and climate change (Birkmann et al. 2022; UN press release, 2021). Currently, both Latin America and Africa are the most socially and economically challenged regions of the world (FAO, 2015; World Bank, 2016; Galli et al., 2022).

A major constraint to livestock production in the Global South is scarcity and fluctuating quality of feed throughout the year (Balehgn et al. 2022; Asaad et al., 2006). Rising prices of feed commodities present a further challenge to this sector, with feed cost currently accounting for 60–70% of total production expenses (Abd El-Hack et al., 2020; van Huis, 2013). Furthermore, 30–40% of food produced today is wasted along the production chain or otherwise fails to reach the consumer (FAO et al., 2022). As a result, many types of organic by-products and livestock manure are produced in large amounts, with negative environmental impacts due to inadequate management (Awasthi et al., 2022; Bortolini et al., 2020). Furthermore, the negative impacts of current production and consumption models associated with the conventional linear economy threaten economic stability, the integrity of natural ecosystems, and social equity (Sanguino et al., 2020).

In the search for achieving a circular economy within the agri-food system while contributing to fulfilling the Sustainable Development Goals (SDGs), insect production allows for closing the nutrient loop while addressing environmental and social problems arising from global agriculture (Hamam et al., 2024). Insects are the most diverse class of organisms, comprising over 50% of all known species (Ballal, 2023), and play a crucial role in maintaining life on Earth due to their significant biomass and the multiple ecosystem services (ESs) they provide (Elizalde et al., 2020; Eilenberg and van Loon, 2018; Losey and Vaughan, 2006), including biological control, pollination, food provisioning, and bioconversion of organic matter (Dangles and Casas, 2019; Van Huis and Oonincx, 2017; Payne and Van Itterbeeck, 2017). Some insect species, such as Black Soldier Fly larvae, efficiently convert low-cost feed or even organic waste into valuable human food and animal feed while providing other ESs. Due to their poikilothermic nature, insects do not actively regulate internal body temperature, allowing them to allocate more energy toward growth and biomass production instead of thermoregulation (van Huis, 2013).

Use of insects as food and feed is increasingly recognized as a viable, sustainable alternative to conventional livestock production, even having a positive impact on the environment as resources which typically go to waste are transformed and reused (van Huis, 2021; Parodi et al., 2020; Lalander et al., 2019; Chia et al., 2019a). Insects are a valuable tool for transitioning to a bio-based circular economy in the agri-food sector, thereby closing the loop in agricultural production through recycling and reuse (Madau et al., 2020; Ravi et al., 2019). Edible insect farming is rapidly expanding globally, demonstrating benefits on small, medium, and large scales (van Huis, 2020). For small-scale farmers in the Global South, insects provide significant social benefits and income-generating opportunities (Barragán-Fonseca et al., 2020; Chia et al., 2019b), including environmental, social, and economic benefits to farmers and agri-food systems on all scales (Barragán-Fonseca et al., 2022).

While the Global South's rich entomophagic tradition has involved numerous edible insect species, the black soldier fly (BSF; *Hermetia illucens* (L., 1758)) has recently attracted the most interest globally (Tomberlin and van Huis, 2020). Therefore, the present article presents an exploratory analysis of the insect farming sector in this region, based on surveys of black soldier fly producers, as well as a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis to characterize the sector. This approach

aims to enhance understanding of the structure, capabilities, challenges, and needs of the insect farming sector and assess the prospects of this industry within the Global South.

Insect farming in the Global South

Production and consumption

Over 2 100 species of edible insects have been identified globally, including 735 in Latin America, reflecting the rich tradition of entomophagy among indigenous and peasant communities, particularly in Mexico, Brazil, Ecuador, and Colombia (Data Basin, 2023; van Loon, 2023; Gasca-Álvarez and Costa-Neto, 2022; Jongema, 2017; Costa-Neto, 2015). Similarly, in Southeast Asia and Africa, insect consumption has long-standing deep cultural roots. In Thailand, for example, many insects are incorporated into local dishes, and some are even consumed as delicacies (Deguerry et al., 2023; Hanboonsong et al., 2013). In Africa, insects have been a traditional food source for centuries, preventing nutritional deficiencies (van Huis and Rumpold, 2023; Numbi Muya et al., 2022; Orkusz, 2021), although insect consumption has thus far been perceived differently in different African countries. In general, on a global level indirect insect consumption - by consuming meat from animals that have consumed feed containing insects - has been more widely accepted by consumers than has direct consumption of insects, and therefore, production and use of insects as ingredients in animal feed appears to be more viable than direct insect consumption (Hong and Kim, 2022).

Insect farming methods and practices

Insect production in Latin America is categorized into traditional, commercial, and sustainable economic initiatives. Traditional production involves a wide variety of species, including the grasshopper (*Sphenarium purpurascens* Charpentier, 1842) and the palm weevil (*Rhynchophorus palmarum* (L., 1758); Piña-Domínguez et al., 2022; Cristancho and Barragán-Fonseca, 2011; Cerda et al., 2001). Commercial production is limited to a small number of species, including the domestic cricket (*Acheta domesticus* (L., 1758)), BSF (*Hermetia illucens* (L., 1758)), and yellow mealworm (*Tenebrio molitor* L.; Caparros Megido et al., 2024). Although medium- and large-scale insect producers are not very common in Latin America (Barragán-Fonseca and Llauradó Casares, 2024), those existing have principally commercial goals and use mechanization and automation to produce insects for human and animal consumption.

Cultural acceptance of insect consumption, coupled with their nutritional benefits (van Huis et al., 2013), has fuelled the growth of insect farming in Southeast Asia. Thailand is known throughout the region for its variety of edible insect species, including crickets, palm weevils, weaver ants, giant water bugs, and grasshoppers (Caparros Megido et al., 2024). In Thailand, cricket farming has been carried out since 1997 - predominantly on a small-scale, which could explain why there are so many cricket farmers registered; as of 2020, 27 000 cricket farmers were registered -80% of which were women, and they mainly reared two-spotted crickets, house-crickets, and ground crickets (Nischalke et al., 2020). A recent survey found that 75% of Thai cricket farmers were small-scale (Nischalke et al., 2020), and cricket farming has been found to be relatively profitable (Halloran et al., 2016). Guidelines for cricket farming were released in Thailand in 2017 (National Bureau of Agricultural Commodity and Food Standards, 2017). While India has a long tradition of insect production - predominantly api- and sericulture for honey and silk production, respectively - as well as consumption by many ethnic groups, insect consumption is increasingly being abandoned (Ghosh et al., 2021).

In recent years, the production of insects for use in animal feed in Southeast Asia has increased, principally involving species other than those traditionally consumed as food. A recent survey (Deguerry et al., 2023) indicates that 90% of insect producers raising insects for feed in Southeast Asia principally produce BSF. While in Thailand and other Southeast Asian countries, crickets are produced for human consumption principally by small-scale farmers, production of mealworm and BSF – primarily for animal feed – is predominantly dominated by the private sector (Nischalke et al., 2020).

In Africa, those edible insects which are most widely raised include Black Soldier flies, mealworms, African palm weevils (*Rhyncophorus phoenicis* (Fabricius, 1801)), crickets (*Gryllus bimaculatus* (De Geer, 1773), domestic crickets, and domestic silkworms (*Bombyx mori* (L., 1758); Mba et al., 2018; Tanga and Kababu, 2023), with notable growth in small- and medium-scale operations (Verner et al., 2021). Additionally, the African palm weevil is a prized food in many rural communities throughout Africa's tropical regions (Siddiqui et al., 2023). Palm weevil larvae hatch from eggs deposited by adult weevils inside the trunks of live palm trees. In their natural habitat, these insects commonly grow in various palm species, including oil palms, where they are most prevalent, as well as coconut and date trees (Siddiqui et al., 2023; Lokela et al., 2021). Remarkably, up to 65% of the African palm weevil larva's weight is fat, positioning it as one of the world's most energy-dense foods (Anankware et al., 2021; Elemo et al., 2011).

Sustainable economy initiatives involving black soldier fly farming

Medium-scale businesses principally produce insects for local sale, while large-scale businesses focus on export. Although no exhaustive inventory of medium- and large-scale insect-producing businesses in Latin America exists, Chile, Costa Rica, and Brazil are leaders in terms of scale of production, legislation, and exportation of insect meal, oil, frass, eggs, larvae, and other products using *Hermetia illucens*, some cricket species, and *Tenebrio molitor* (Caparros Megido et al., 2024; Bermúdez-Serrano, 2020). One interesting sustainable insect farming initiative in Latin America is the National University of Colombia's "Insects for Peace" project, which provides a model for sustainable insect farming. This project is aimed at reducing the cost of commercial feed using BSF to feed fish and other farm animals and providing a livelihood for ex-combatants (Barragán-Fonseca et al., 2020).

Rural communities in the Global South produce *Hermetia illucens* and other insect species to reduce the cost of feed for fish and other farm animals. The "Insects for Peace" project illustrates how farmers can establish profitable circular agricultural initiatives involving insects, enabling them to access markets in the Global South and providing them with socioeconomic benefits that significantly improve their livelihoods and food security (Barragán-Fonseca et al., 2023; Chia et al., 2019b). Barragán-Fonseca and Llauroad Casares (2024) analyzed two surveys conducted with members of the Latin American Association for Animal Production (ALPA) to assess the state and potential of insect farming. The surveys highlighted strong interest in cultivating *Hermetia illucens* and *Tenebrio molitor*, with respondents identifying the need for more training, technical support, and value chain development to expand the industry.

Southeast Asia has several large-scale *Hermetia illucens* producers. Entobel – established in 2013 in Vietnam (<https://www.entobel.com/>) – began construction in 2022 of what is projected to become Southeast Asia's largest *Hermetia illucens* plant, which will be fully automated and have the capacity to produce 10 000 tons of *Hermetia illucens* larvae meal annually. Other Southeast Asian companies producing *Hermetia illucens* larvae on different types of agro-industrial side-streams include Nutrition Technologies, established in Malaysia in 2015 (<https://www.nutrition-technologies.com/>); Protenga, established in Singapore in 2017 (<https://www.protenga.com/>); and Biocycle, established in Indonesia 2018 (<https://biocycleindo.com/>). In addition to using *Hermetia illucens* larvae in animal feed, technology has been explored for using this insect for waste management in many Asian countries (Kim et al., 2021). For instance, the Swiss Federal Institute in Aquatic Research (EAWAG according to its German initials) has piloted a research facility in Indonesia aiming at using *Hermetia illucens* for waste management purposes (Zurbrugg et al., 2018).

In Africa, projects supported by organizations including the Norwegian Agency for Development Cooperation (NORAD) and the International Institute of Tropical Agriculture (IITA) are aimed at increasing income generation and improving people's livelihoods through BSF-based technology (Dzepe et al., 2024; NORAD, 2022; Terfa, 2021). Such initiatives have demonstrated the socioeconomic benefits and contributions to food security of insect farming (Barragán-Fonseca et al., 2023; Chia et al., 2019b). Amid Africa's broad diversity of ecosystems, a growing agricultural revolution is redefining the boundaries between tradition and innovation. Insect farming – once deeply rooted in indigenous knowledge – is now at the forefront of sustainable solutions to the pressure placed on natural resources caused by conventional agriculture (van Huis et al., 2021). According to a World Bank report (Verner et al., 2021), insect farming – as well as hydroponics – has significant potential to mitigate undernourishment affecting numerous communities across Africa.

According to World Bank report, insect, and hydroponic farming hold significant potential in mitigating the prevalent issue of undernourishment affecting numerous communities across Africa. Presently, approximately, 850 insect farms have been established within 10 out of 13 surveyed countries on the continent, highlighting a growing recognition and adoption of these innovative agricultural practices (Verner et al., 2021). This number is projected to surge, potentially doubling, should an extensive survey encompass all 54 nations on the continent. Highlighting an innovative use of agricultural by-products as rearing substrates, the report underscores the capacity of insect farming to generate approximately 2.6 billion U.S. dollars in insect CP and an additional 19.4 billion dollars from organic fertilizer annually. Moreover, this burgeoning sector holds the promise to supply up to 14% of the CP requirements for rearing essential livestock, including pigs, fish, and poultry, across Africa, marking a significant stride toward self-sufficiency and nutritional security (Verner et al., 2021).

Over the past decade, several insect farms have sprung up across Africa, most of which principally raise BSF due to its high prolificacy and biological potential to efficiently recycle a wide range of organic materials into nutrient-rich biomass (Dzepe et al., 2023). Africa is recognized among the top regions of the world interested in breeding BSF, which may be attributed to the fact that insects have long been incorporated into food and feed throughout most of the continent (Kipkoech et al., 2023). Annually, BSF farming alone could potentially replace 60 million tons of conventional feed produced in Africa, where the total animal feed production was estimated to be 51.42 million metric tons in 2023 (Alltech, 2024). This potential replacement represents approximately 116.7% of the total animal feed production for that year. Additionally, approximately 200 million tons of crop waste could be recycled using BSF larvae as bio-converters, producing approximately 60 million tons of organic fertilizer while directly and indirectly creating 15 million jobs throughout the continent (Verner et al., 2021). This potential recycling represents approximately 114.9% of the most recent estimate of 174 million tons of organic waste generated (Adedara et al., 2023). Similarly, BSF farming could prevent 86 million tons of carbon emissions annually, equivalent to removing 18 million vehicles from the roads in the continent (Verner et al., 2021). Insect co-products, particularly frass derived from BSF larvae production, are increasingly being used

as fertilizer (Terfa, 2021). Frass from nine insect species – including BSF, mealworms, and crickets – has been demonstrated to be nutrient-rich, therefore highly suitable for fertilizing crops (Chavez et al., 2024; Beesigamukama et al., 2022; Dzepe et al., 2022). Quilliam et al. (2020) have shown that frass from BSF larvae reared on various types of organic waste streams is comparable to synthetic NPK fertilizer with respect to crop yield.

Challenges and potential of insect farming

Insect farming in the Global South faces numerous challenges. Despite the many benefits of insect farming, in Africa, it is still a new industry, and limited research and scientific knowledge hinder its growth (Tanga et al., 2021). The need for industry regulation to overcome variation in legislative frameworks among nations is a pressing challenge. Surveys conducted by the ALPA reveal interest in insect production in Latin America but highlight gaps in stakeholders' awareness of existing legislation (Barragán-Fonseca and Llauroad Casares, 2024). Deguerry et al. (2023) argue that in Southeast Asia, while regulatory diversity offers opportunities, standardization is crucial for industry growth, and propose initial steps toward standardization, including identifying those actors which should be responsible for this task as well as those species which have already been authorized in certain nations, and fostering regional collaboration. In Southeast Asia, regulations dictating insect industry standards vary from nation to nation (Deguerry et al., 2023). For instance, Thailand introduced cricket farming guidelines in 2017, yet no other country in the region has adopted them. This may be due to the underdeveloped cricket farming industries in regions such as Cambodia and Laos, where informal farming methods dominate, alongside variations in consumer demand and cultural acceptance of insect farming (Halloran et al., 2018a, b). In 2022, Singapore passed regulations for *Hermetia illucens* and other authorized insect species, focusing primarily on their safe use in food and feed, while providing general guidelines for production hygiene but not detailed standards for the farming process itself (Singapore Food Agency, 2022).

Research initiatives and industry growth

Several projects and surveys highlight the growth as well as challenges of insect farming. In Latin America, surveys by ALPA show interest in species including *Hermetia illucens* and *Tenebrio molitor* and that respondents advocate for collaborative efforts to foment insect farming (Barragán-Fonseca, 2024). In Southeast Asia, large-scale BSF producers, including Entobel and Nutrition Technologies, principally use insects to produce feed and manage waste (Kim et al., 2021; Zurbrugg et al., 2018). However, a survey conducted in Afghanistan, Bangladesh, and China (Salam et al., 2023) found that public acceptance of using insects as feed was greater than that of using them for waste management. Those carrying out the survey attributed resistance to insect-assisted waste management to a lack of knowledge with such technology. In Africa, “research for development” projects by NORAD and IITA have aimed at scaling technology for farming BSF, with promising results for producing livestock feed and organic fertilizer (Dzepe et al., 2024; Norad, 2022; Verner et al., 2021; Chia et al., 2019a, 2021; Adeoye et al., 2020).

Methodology

Survey design and distribution

In order to analyze the state of insect farming with a focus on BSF production in the Global South, in 2024, we designed and distributed a comprehensive survey to BSF production facilities in

Latin America, Africa, and Asia. The survey included the following sections: general information (facility name, address, contact person, establishment date, and operational status), biowaste substrate (types and costs of substrates used, initial and current biowaste processing capacity), products (types of products, processing methods, customer segments, product pricing, production volume, and revenue), costs (total weekly labor hours and salary; number of employees; initial investment in infrastructure, machinery, and materials; and operational costs), and other experiences (additional insights shared by facility operators).

Survey distribution and gathering responses

The survey was distributed electronically to over 100 BSF producers throughout the targeted regions by email, social media, professional networks, and other channels to insure broad outreach. Approximately, 30% of the surveys were sent to Africa, 30% to Latin America, and 40% to Asia to reflect the region's higher concentration of BSF producers. Follow-up reminders were sent to increase the response rate. Nevertheless, completed surveys were received from only 33 facilities: 14 from Africa, 4 from Latin America, and 15 from Asia. Three of the surveyed facilities in Africa did not provide information on the amount of waste they processed per week.

In-depth interviews

In addition to the surveys, we also conducted in-depth interviews with a subset of respondents selected based on the authors' prior knowledge of the companies or closer professional contacts, making it easier to access and engage with these producers. The goal was to gather additional insight into operational challenges and opportunities faced by BSF producers, and thereby obtain qualitative information regarding a broader context to inform our analysis.

Data compilation and analysis

Survey responses and interview data were compiled into an Excel file for systematic analysis, and quantitative data were tabulated. Qualitative responses were coded and categorized to identify recurring themes and insights.

Strengths, weaknesses, opportunities, and threats analysis

To comprehensively assess the strengths, weaknesses, opportunities, and threats of BSF farming in the Global South, the authors of the present article conducted a series of meetings to analyze the survey data, taking advantage of their collective experience. The SWOT analysis identified factors internal to the farming operation that provide advantages (strengths) and those that limit or present challenges to its further development (weaknesses), as well as external factors that could be taken advantage of to improve and increase the scale of operation (opportunities) and those that pose risks to its success and sustainability over time (threats). The analysis incorporated insights from survey responses, in-depth interviews, a literature review, and the authors' extensive field experience in different regions of the Global South, to provide a comprehensive and informed understanding of the BSF farming landscape.

Results and discussion

Analyzing black soldier fly production in the Global South: insights from surveys

Of the 100 surveys distributed, a completed survey was received from 33 BSF producers in 13 countries on three continents

of the Global South. In Africa, 14 producers were surveyed, from Uganda, Kenya, Ghana, Cameroon, Togo, Benin, Rwanda, and Tanzania. In Asia, one producer in India and 14 in Indonesia were surveyed. In South America, three producers in Colombia and one in Brazil were surveyed. Those facilities that responded were predominantly small-scale (producing up to 2 tons of fresh larvae per week; Fig. 1), except for one facility in Asia and another in Africa which produced 35 and 56 tons of larvae per week, respectively. Despite the small sample size, the varying scale of production found for BSF operations concurs with that previously reported in the literature, which identified a range of small-scale production for family-consumption - even cultivating larvae in buckets in the kitchen - to industrial processing of tons of waste daily (Barragán-Fonseca et al., 2023; Mahmood et al., 2021; Joly and Nikiema, 2019; Nyakeri et al., 2017).

Those surveyed use a wide range of substrates (Fig. 2). African facilities employed the widest variety of waste materials, including vegetable and brewery waste, pig and poultry manure, household biowaste, and dairy industry waste. The relatively low diversity of substrates observed in Latin America may be attributed to the small number of facilities surveyed. Notably, Asian producers refrain from using manure as a substrate for larvae, perhaps due to cultural resistance. Despite the variety of substrates used, some producers reported difficulty in securing a stable supply.

While respondents principally marketed fresh larvae to be raised by other producers, as well as frass, those products offered varied notably (Fig. 3), including dried whole and ground BSF larvae, BSF full-fat and defatted larvae meal, and BSF eggs. African producers principally dried the larvae through solar methods, while microwaves, ovens, and other methods were used in Latin America and Asia. In Asia, a popular product appeared to be popped larvae, prepared by heating larvae to a high temperature using a microwave or frying pan, causing the larvae to pop. In Asia, many producers mix frass with garden compost to sell a mixed organic soil amendment. Most producers surveyed in Latin America and Africa sell fresh frass for use as fertilizer. Apparently, BSF larvae producers in the Global South do not currently produce potentially profitable value-added ingredients for the pharmaceutical and cosmetic industries (Rabani et al., 2019).

Fig. 4 provides a general description of the responses to our survey, including notable similarities and differences in responses. One noteworthy commonality among many producers surveyed was that they decided to rear BSF for environmental reasons, either

to treat waste or produce more sustainable feed. Common challenges reported by many producers surveyed included navigating regulatory hurdles, insuring consistent insect quality, and securing sufficient amounts of waste of acceptable quality. Due to variation in available substrate - which impacts composition of the larvae - it is difficult to achieve consistent product quality (Lalander and Lopes, 2024). Higher quality waste must often be purchased (e.g. grain waste from breweries and press cakes) and is often used directly as animal feed. Lower-quality waste which is more readily available in large volumes, such as fruit and vegetable peels and other types of market and food processing waste, are not ideal for rearing BSF larvae. Several authors have acknowledged this challenge, recommending a combination of a variety of types of waste streams in order to fulfill BSF larvae's nutritional needs (Isibika et al., 2023; Gold et al., 2021). In fact, many producers surveyed already combine a variety of waste sources (Fig. 2). However, combining a variety of waste streams complicates the production process, as more stakeholders are involved. Other challenges reported are scaling up production to meet the high demand for animal feed, as well as the difficulty of competing with the price of fish and soymeal-based feed. One way of meeting this challenge and increasing income is to produce products for the global market, particularly pet feed. In fact, this is a global trend, as approximately 50% of the global dry weight of insects produced is used in pet food, which only constitutes 3% of the total market for animal feed (van Huis and Gasco, 2023). Four respondents indicated that they had ceased operations, for example due to a lack of market demand, insufficient funding sources, operational difficulties with machinery, and obtaining and maintaining qualified staff.

Morseletto (2023) found that historically, scarcity in general has favored circular practices involving the reuse of waste, while unutilized waste increases in times of excess. Circular systems are more complex than linear systems, and transitions to circular economies generally require radical changes in all parts of the system - including management, production, and consumer habits - in order to minimize loss of value throughout the chain (Iacovidou et al., 2021). To meet these challenges, Iacovidou et al. (2021) recommend a holistic approach to insect production that addresses the root cause of problems, which encompasses political, environmental, technical, social, and other aspects of resource management. Some challenges associated with transitioning to a circular economy have been experienced by the producers surveyed for the present study, for example trying to compete with low-cost

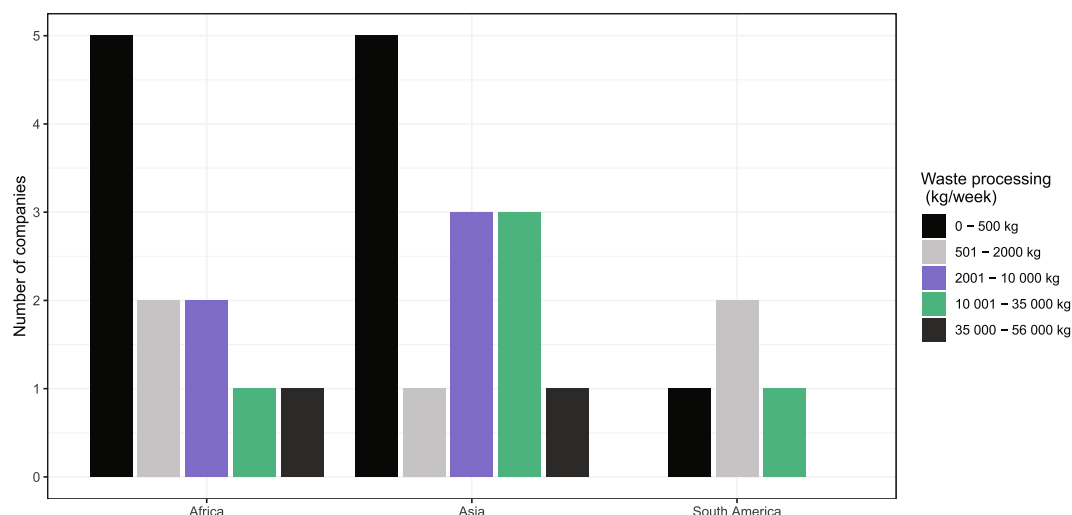


Fig. 1. Distribution of insect producers surveyed across three continents and the corresponding volume of waste processed by facilities able to provide this information: Africa (n = 11 (of 14 surveyed)), Asia (n = 13), and South America (n = 4).

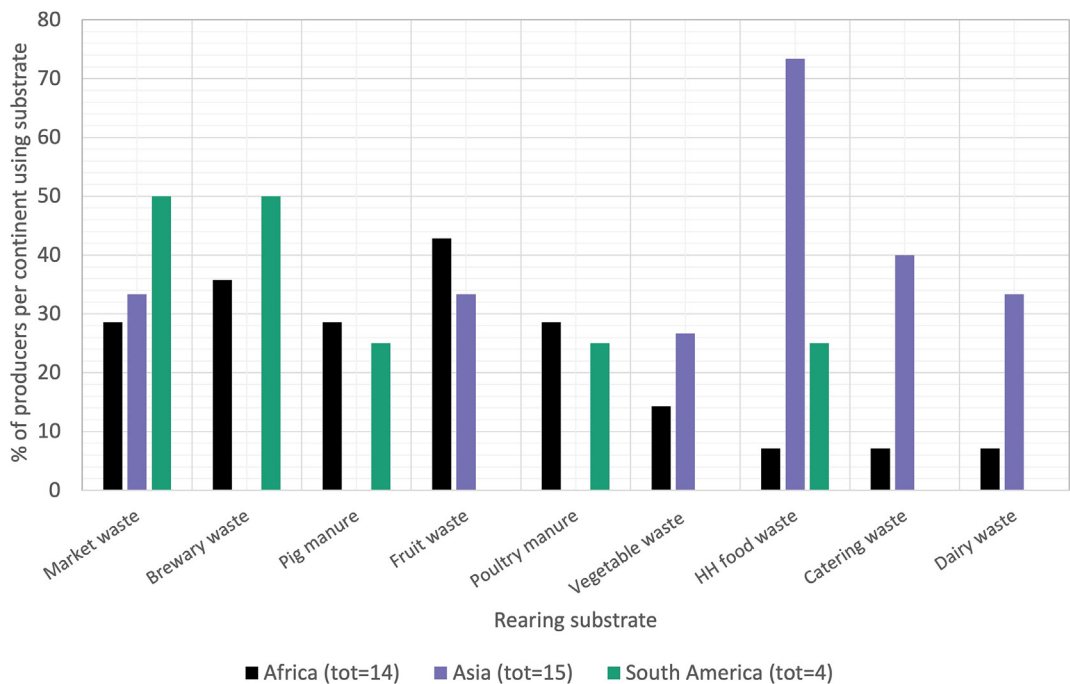


Fig. 2. Substrates used by insect producers of three continents surveyed. HH = House-hold food waste.

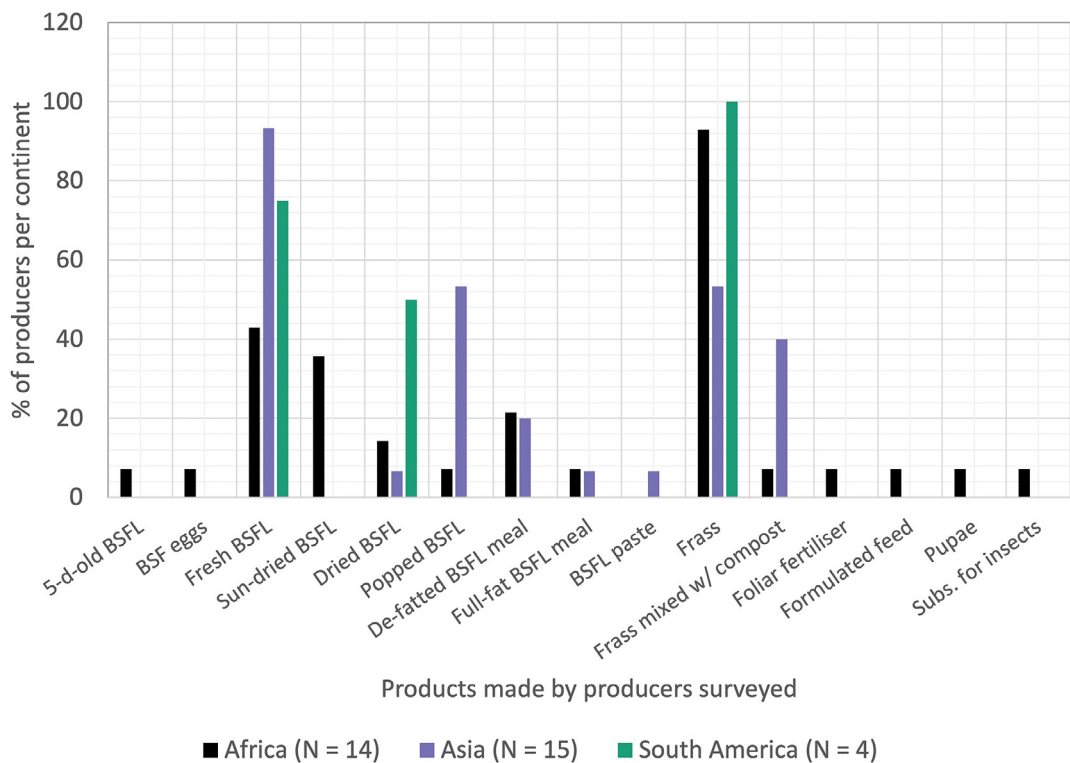


Fig. 3. Percentage of insect producers surveyed on three continents who make different products. BSFL = black soldier fly larvae; Subs. = substrate for BSFL rearing.

products produced using linear processes and dealing with insufficient or inconsistent regulations.

Strategic assessment of insect farming in the Global South

Based on a literature review and the information obtained from the surveys, we carried out an analysis of the strengths, weak-

nesses, opportunities, and threats of insect farming in the Global South (Fig. 5).

Strengths

Insect farming in the Global South has several strengths that contribute to its environmental sustainability and economic viability. The high diversity of edible insects and rich entomophagic tra-

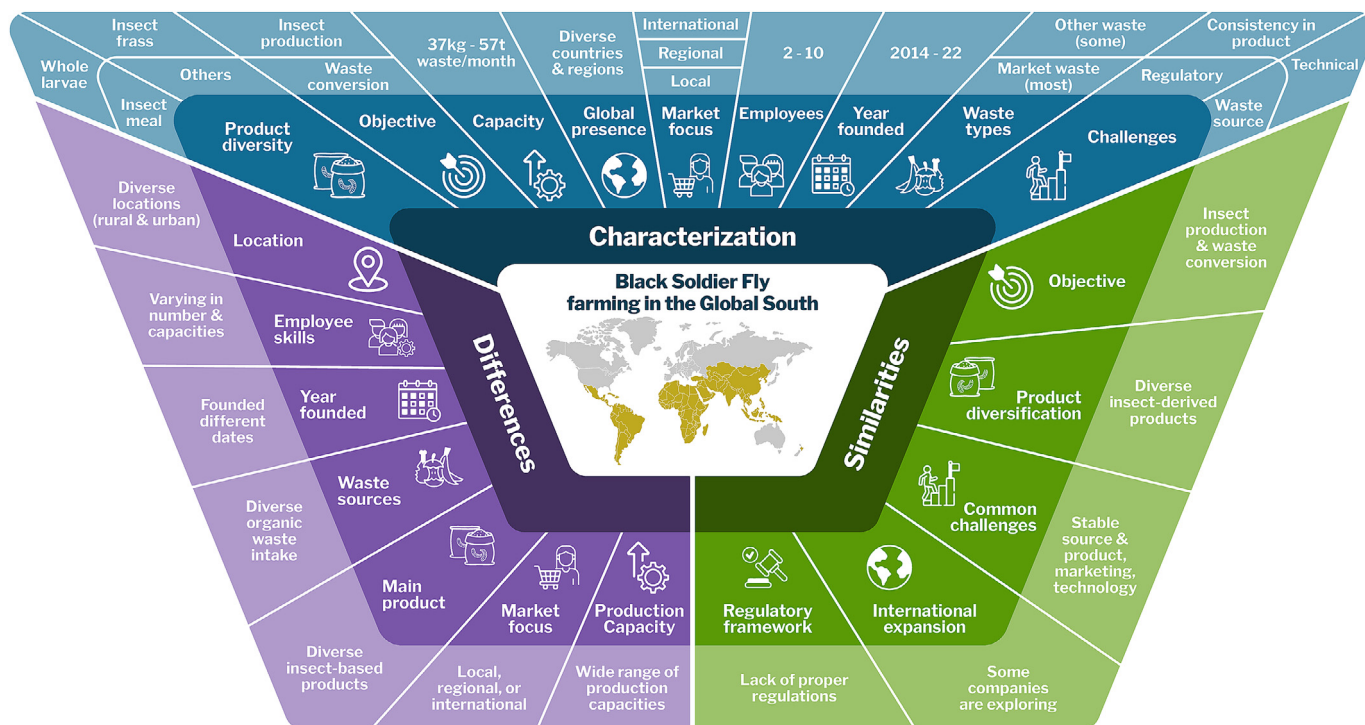


Fig. 4. Characterization of Black Soldier Fly Farming in the Global South: Highlighting Facility Features, Similarities, and Differences.

dition, which have led to deep-rooted cultural acceptance of insect consumption in some parts of the region, facilitate sustainable insect collection and production as well as adoption of insect farming as a mainstream agricultural activity, thereby promoting food security and enhancing environmental sustainability. Additionally, the Global South – particularly those nations with the lowest average - income - benefits from favorable climatic conditions for insect rearing, which not only favor the natural proliferation of insect populations but also reduce energy and resource inputs required for artificial rearing, in turn, favoring cost-effectiveness and environmental sustainability.

Small-holder farmers are the primary actors in the insect farming sector in the GS. Their traditional knowledge and experience, coupled with the availability of locally sourced materials and substrates, enable low-cost production. Unlike large-scale high-tech facilities in the Global North, small-scale operations offer flexibility and adaptability to local resources and community needs, making them resilient and sustainable contributors to the industry. Insects have also been found to deactivate selected disease-causing microorganisms (Lopes et al., 2020; Lalander et al., 2015) and chemical residues (Hoffman et al., 2024). Thus, simple insect-based technology could significantly improve the biological and chemical safety of recycling organic waste streams back into the food system using simple methods, particularly benefiting regions of the Global South which lack waste management infrastructure. BSF technology, in particular, could serve as a means of waste management on a large scale (Rehman et al., 2023).

The diversity of edible insects in the Global South offers a range of environmental, social, and economic opportunities (Barragán-Fonseca and Llauredó Casares, 2024; Berggren et al., 2019). Research and bioprospecting – seeking nature-based solutions – would facilitate taking advantage of these opportunities. Collaboration among government, the private sector, farmer and insect producers' associations, and academia is key to identifying and developing value chains for insects and establishing effective reg-

ulatory frameworks governing the search for species useful for food, feed, and other ecosystem services in accordance with the Convention on Biological Diversity and the Nagoya Protocol in order to avoid legal problems and protect biodiversity and traditional knowledge (Ballal, 2023; Srivastava, 2017).

The high level of biomass production in the Global South results in an abundance of substrates and organic waste which may serve as inputs for insect production. Such availability of substrates significantly reduces production costs, thereby enhancing the economic viability of insect farming. Moreover, easy access to inexpensive locally available materials for building infrastructure further lowers entry barriers for small-scale farmers. Additionally, in some nations of the Global South (e.g. Colombia and Kenya), research institutions actively contribute to the development, dissemination, and implementation of effective insect-rearing practices. Unlike large-scale operations in the Global North, which are often technology-driven, small-holder farmers rely on local networks and partnerships for the development of their practices, making them more suitable for rural and low-resource settings. Finally, the region's peasants and other small-scale farmers possess a wealth of indigenous and traditional knowledge which may provide valuable insights with respect to insect farming techniques and feed formulations, thereby enriching the sustainability and resilience of insect farming systems in the Global South.

Weaknesses

Insect farming in the Global South has several weaknesses that hinder its widespread adoption and growth as a sustainable agricultural practice. The current limited scale of insect production poses a significant challenge to the industry's growth potential. The limited size and informal nature of many small-holder insect farms make scaling up difficult. As manual processes increase labor costs, automation is essential to achieve economies of scale (van Huis, 2022b; Halloran et al., 2018a,b). Moreover, inadequate insect farming and processing technology limits the value-added poten-

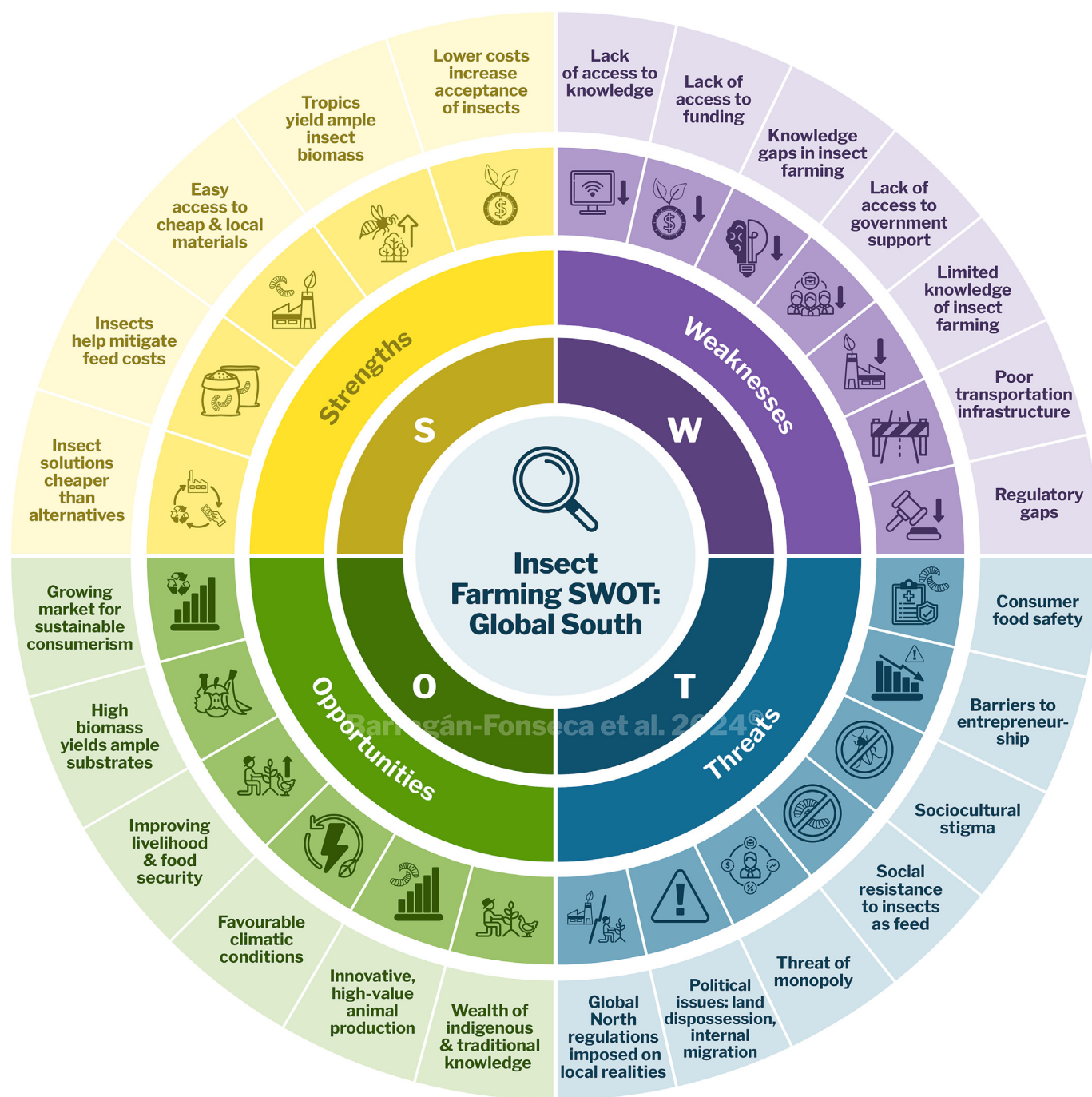


Fig. 5. Analysis of strengths, weaknesses, opportunities, and threats (SWOT) of insect farming in the Global South.

tial of insect-based products, as well as their marketability and commercial viability. Furthermore, the lack of specific regulations governing insect farming leads to uncertainties regarding legal compliance with other laws – for example regarding the production of animal feed – as well as market acceptance. Additionally, insuring high-quality homogenous inputs is crucial as variability in the types and quality of organic waste used as feed for larvae impedes consistency and limits the quality of insect products (Lalander and Lopes, 2024; Lundy and Parrella, 2015).

Gaps in knowledge regarding various aspects of insect production – including rearing techniques, processing methods, and animal feed formulation – impede the industry's development. Furthermore, lack of access to funding sources – particularly by

small-scale farmers – impedes investment in infrastructure, equipment, and research essential for scaling up insect farming operations. For example, the absence of government support limits availability of financial incentives, technical assistance, and regulatory frameworks necessary for fostering the development of insect farming. Furthermore, poor transportation infrastructure, makes it difficult to obtain inputs and efficiently distribute insect-based products to markets.

Environmental and health concerns in insect farming include the accumulation of synthetic and natural chemicals in insects' bodies, and potential allergies when consumed, as well as disease transmission (Lalander and Vinnerås, 2022; van Huis and Oonincx, 2017). Insuring safety requires thorough investigation

and maintenance of high-quality biomass (Lalander and Lopes, 2024). Implementing management and safety systems such as the Hazard Analysis and Critical Control Point system (Arévalo Arévalo et al., 2022) is crucial. Moreover, the lack of access to information technology and technical and scientific knowledge in rural areas limits farmers' ability to adopt innovative practices and technologies, in turn hindering the sector's overall growth and competitiveness. Finally, the "de-peasantization" of some regions in the Global South due to violence, dispossession of land, internal migration, and other socio-economic factors diminishes farmers' willingness to engage in agriculture, further undermining the potential of insect farming as a sustainable livelihood option in regions affected by such phenomena.

Opportunities

Insect farming presents significant opportunities for socioeconomic development in the Global South. It offers small-scale farmers the potential to diversify and thereby improve their food security as well as tap into new markets and income sources to improve their livelihoods, particularly in rural areas where traditional agricultural practices result in limited profitability. By cultivating edible insects, entire communities can enhance their access to nutritious food sources while also generating surplus for sale or trade, thereby bolstering their economic resilience.

Insect farming in turn facilitates the development of other types of innovative animal production systems, adding value. The growing global emphasis on the need for ecologically sustainable agricultural practices has led to a burgeoning market demand for alternative protein sources. Insect-derived proteins offer a promising solution, particularly as components for animal feed, especially in rural regions where commercial feed costs are prohibitively high. By incorporating insects into feed formulations, the cost of livestock and fish production may be significantly reduced, making their production more accessible to residents of villages and small cities. Additionally, insect farming presents a sustainable form of organic waste management, as it uses large quantities of substrates to rear insects, thereby contributing to environmental conservation and a circular economy.

Farming BSF larvae, in particular, presents a potential solution for farmers in the Global South to the critical shortage of affordable, high-quality, high-protein feed that has long constrained the expansion of livestock and fish farming in the region (Obiero et al., 2019; Wong et al., 2017). In terms of protein content, BSF larvae rival traditional feed sources such as fish meal and soybean meal (Gougbedji et al., 2022). BSF larvae meal not only serves as a locally sourced feed ingredient but also promotes environmental sustainability as its production involves upcycling organic waste, thereby reducing reliance on conventional feedstock and minimizing agricultural waste, and in turn supporting local economies (Gold et al., 2021).

Thus, through insect farming, tropical nations could reduce food and feed production costs and energy consumption. However, more research is needed regarding its viability (Barragán-Fonseca et al., 2023) in order to promote widespread large-scale insect production. Existing alliances within the insect production sector in the Global South seek to foment collaboration and knowledge exchange regarding insect production. Implementation of regulations such as those already in effect in European nations is crucial to guaranteeing food safety related to insect production (Arévalo Arévalo et al. 2022; IPIFF, 2019).

Threats

Insect farming in the Global South faces numerous threats that impede its growth and sustainability. In countries with little tradition of entomophagy, social and cultural stigma surrounding insect

consumption limits consumer acceptance of insect-based products – particularly in urban areas – and inhibits market demand and economic viability of insect farming ventures. Along with this, social resistance to replacing traditional animal feed with insect-derived alternatives poses a formidable challenge to widespread adoption of insect farming, particularly by livestock farmers, who may be reluctant to deviate from conventional feed sources. Thus, there is a need to raise awareness regarding insects as food and to scale up insect production in the Global South.

Additionally, there is a risk of market domination by large-scale, industrialized producers from the Global North, who have more resources and advanced technologies. This could limit market access for small-scale producers, undermining their presence and economic viability. Without supportive regulations tailored to small-scale producers, they remain vulnerable to external competition and exclusion from key markets. Despite traditions of entomophagy in many parts of the Global South, sales of insect-based products remain local (Olivadese and Dindo, 2023). Innovative strategies are needed to overcome public resistance to insects as potential human food and livestock feed, as well as providers of ecosystem services (Barragán-Fonseca, 2024; Verbeke, 2015).

The insect production sector of the Global South is also vulnerable to becoming subject to regulations originating from the Global North (Lalander and Vinnerås, 2022). For example, the EU's strict feed regulations require specific processing standards for insects to be used in animal feed, which can be prohibitively expensive for small-scale producers in the Global South, favoring larger industrial operations instead. This could undermine artisanal production, and promote intensive, industrialized models that are ill-suited to local realities. Furthermore, in some countries, control over territories due to organized crime and other types of conflicts and illegal activities poses significant threats to the stability and security of insect farming operations. Additionally, there is a major possibility of monopolization of the insect farming sector by large corporations and other influential actors, limiting market competition and impeding participation by small-scale farmers.

The aggressive economic structure of some nations also presents challenges for entrepreneurial farming initiatives, exacerbating inequalities and hindering the development of inclusive, sustainable insect farming systems. Furthermore, food safety concerns – including issues related to hygiene, quality control, and potential allergies to insect-based products – pose significant threats to market acceptance and regulatory compliance, undermining long-term viability of insect farming in the Global South.

Insect producers surveyed highlighted insufficient local regulatory frameworks, complicating safety standards, impeding innovation (van Huis, 2022a; van Huis and Oonincx, 2017), and hindering the expansion of insect farming (Dobermann et al., 2017). While some Global South nations are establishing regulations, most lack regulatory frameworks. Collaboration among government, the private sector, and academia is crucial to establishing effective regulatory frameworks to address this issue (Caparros Megido et al., 2024; Dicke et al., 2020).

Conclusions

The global ecological and socioeconomic functions of insects are of vital importance for overcoming many current challenges to agrifood systems, including deteriorating natural resources, rising costs of agricultural inputs, and the high rate (30–40%) of food waste in chains of production, and thus use of insects as food and feed contributes to several SDGs and to improving the livelihoods of small farmers (Barragán-Fonseca et al., 2020; Chia et al., 2019b; Dicke, 2018). Despite their potential to contribute to sus-

tainable food production, insect farming in the Global South faces several interrelated challenges regarding management practices involved in insect production and transformation, biosafety, marketing, and legislation (Barragán-Fonseca and Llauradó Casares, 2024; Dicke et al., 2020). Substrate stability and scaling up technologies are also significant challenges.

Africa and Asia have a significant number of small-scale insect farms, whereas in Latin America, there appears to be a greater reluctance to using insects as food (Costa-Neto, 2015), which has resulted in a lower number of producers. Nevertheless, information regarding insect producers in Latin America is limited, which may be a result of lack of organization within the sector, perhaps reflecting the smaller number of producers due to legislative and other challenges. Organization within the insect-producing sector may be more advanced in Africa and Asia, where the International Centre of Insect Physiology and Ecology, the Association of South-east Asian Nations, and other organizations could potentially play important roles in the development of the insect farming sector (Tanga et al., 2021; Surendra et al., 2020). However, the landscape of global insect production appears to be evolving. For example, Costa Rica is establishing a legal framework for insect producers (Bermúdez-Serrano et al., 2023); the Latin ALPA recently established an insect production chapter; and a private initiative called Apical has compiled contact information from several producers in the region (Aliados/Apical, n.d.).

While the production and use of insects as food and feed is growing incipiently in the Global South, it has significant potential to contribute to the region's food security, sustainability, and economic development. Collaboration between the Global South and the Global North may allow for exploring the potential of insects contributing to ecosystem services and sustainability of agrifood systems worldwide. Incorporating insects into agrifood systems, particularly on a larger scale, requires promoting knowledge exchange and collaboration among producers, academia, and legislative bodies (Barragán-Fonseca, 2024).

While insect farming may contribute to sustainable agriculture, its success relies on overcoming challenges with respect to regulations, technology, input quality, consumer acceptance, health, and safety. These issues must be addressed through more complete regulatory frameworks tailored to each specific region, technological innovation, rigorous quality control, effective marketing, and extensive research regarding health and safety. Global collaboration among stakeholders - including policymakers, researchers, and industry leaders - will be crucial to advancing this emerging industry.

Ethics approval

Not applicable.

Data and model availability statement

The data are not in an official repository. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

The authors declare that they have no conflict of interest.

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Transparency Declaration

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