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Insect-based organic waste management: a sustainable pathway to enhanced ecosystem services and food security

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Insect-based organic waste management (IBOWM) is revolutionary for tackling organic waste disposal and fostering sustainable food production. This review examines the multifaceted benefits of IBOWM, including its capacity to reduce landfill waste, decrease greenhouse gas emissions, and improve soil health through the practical application of nutrient-rich insect frass. A major contribution of this study is developing a comprehensive framework that illustrates how insect farming enhances ecosystem services by bolstering biodiversity and optimizing nutrient cycling. Drawing on current research and diverse regional case studies, the paper highlights successful IBOWM implementations while also identifying major challenges such as regulatory barriers and public acceptance issues. The economic implications are also explored, with an emphasis on job creation and sustainable livelihoods, particularly in rural communities. Additionally, the review underscores the critical need for supportive policies and harmonized regulatory frameworks across regions. Finally, future research directions are outlined, stressing the importance of standardized regulations, thorough economic assessments, and targeted public education initiatives. By creating a supportive environment for IBOWM, stakeholders can significantly advance sustainable waste management, enhance food security, and promote overall ecological health, ultimately paving the way for a more sustainable future.

KEYWORDS

ecosystem services, insect farming, inset-based organic waste management (IBOWM), regulatory frameworks, sustainable food production, waste reduction

Highlights

- IBOWM reduces landfill waste and lowers greenhouse gas emissions
- Insect frass enhances soil health and supports nutrient cycling
- The framework illustrates how insect farming boosts ecosystem services
- Economic benefits include job creation and sustainable livelihoods
- Direct new research toward regulations and enhancing public education

1 Introduction

Managing organic waste, such as food residues, plant materials, and agricultural byproducts, poses significant challenges to environmental sustainability (Doughmi et al., 2024). Rapid urbanization and population growth have led to a dramatic increase in organic waste production, resulting in resource depletion, greenhouse gas emissions, and the contamination of land and water resources (Bian et al., 2024; Li R. et al., 2023; Serafini et al., 2023). Improper disposal practices often release methane, a potent greenhouse gas that contributes to climate change, while many municipalities continue to struggle with effective waste segregation and treatment (Salemdeeb et al., 2018; Oliveira et al., 2017).

A further challenge in organic waste management is transforming public perceptions so that waste is seen as a valuable resource rather than as refuse destined for landfills. Although educating households on how food waste harms the environment fosters greener behavior, inadequate infrastructure and resources lead many communities to remain reliant on unsustainable methods such as landfilling and incineration (Jereme et al., 2016; Starostina et al., 2014). Moreover, waste-sorting policies, while potentially effective, often encounter resistance because of limited public engagement and understanding (Liu et al., 2024). Economically, the costs associated with waste collection, transportation, and treatment are substantial, particularly for municipalities with limited financial resources (Yalçınkaya and Kırtıloğlu, 2019). Although integrating composting and anaerobic digestion can reduce these costs and enhance resource recovery, their success depends on a comprehensive understanding of local conditions and active community involvement (Haupt et al., 2018; Sfetsas et al., 2023).

Ecosystem services like food, water, climate regulation, and nutrient cycling are crucial for sustaining environmental balance and human well-being (Costanza et al., 2014; Morimoto, 2020). In this context, insect-based organic waste management (IBOWM) emerges as a promising strategy that enhances these services. IBOWM harnesses specific insect, primarily black soldier fly (BSF) larvae and to a lesser extent, oil palm weevil larvae, to convert organic waste streams. These include poultry litter, catering leftovers, and agricultural byproducts, which are transformed into protein-rich insect biomass, organic frass biofertilizers, and renewable energy feedstocks (Kullan et al., 2024). By leveraging the larvae's robust digestive capabilities and their symbiotic gut microbiota, this bioconversion process, sometimes termed entomoremediation, reduces waste volume while repurposing it following circular economy principles (Eke et al., 2023). This strategy enhances nutrient recycling and mitigates greenhouse gas emissions compared to traditional landfill practices (Ţucă and Stan, 2023; Siddiqui et al., 2024).

Moreover, converting waste into high-value resources bolsters food security and exemplifies a circular economy, wherein waste materials are repurposed as inputs for new products (Reynolds et al., 2022; Hawkey et al., 2021; Vrontaki et al., 2024). Meeting global sustainability targets hinges on integrating IBOWM into waste management systems as urbanization and food production pressures intensify (Hilo et al., 2024; Czekała et al., 2020). In addition, IBOWM has the potential to invigorate local economies by creating jobs within waste management and insect farming sectors, while also promoting community engagement in sustainable practices (Oktaviani et al., 2023; Kovalenko et al., 2024). Ongoing technological and research advancements will further boost IBOWM's efficiency. This positions IBOWM as a critical strategy for addressing environmental challenges, fostering economic growth, and enhancing food security making it a prime target for future research and policy initiatives (Mouhrim et al., 2023; Ites et al., 2020).

This review explores novel aspects and identifies critical research gaps pivotal to advancing IBOWM. It presents a comprehensive framework that elucidates how IBOWM enhances ecosystem services, spanning waste reduction, nutrient cycling, biodiversity support, and climate change mitigation, a perspective that has largely been overlooked. By incorporating regional case studies of successful IBOWM applications, the study bridges the gap between theory and practice, thereby offering actionable insights for both stakeholders and policymakers. Furthermore, it highlights the economic benefits, such as sustainable job creation, and emphasizes the necessity for robust regulatory frameworks to overcome market access barriers and ensure the safe production of insect-based products. In doing so, the review makes a compelling case for the role of IBOWM in sustainable waste management, food security, and livelihood improvement.

In response to the urgent need to manage escalating organic waste sustainably, this study examines IBOWM as an innovative solution that harnesses insects to convert organic waste into value-added products like protein-rich biomass and organic fertilizers. By reducing greenhouse gas emissions, decreasing landfill dependency, enhancing soil health, and supporting biodiversity, IBOWM contributes to a circular economy in which waste is repurposed as a resource. This review is guided by three clear objectives: first, to assess IBOWM's environmental, economic, and social benefits, including waste reduction and ecosystem enhancement; second, to build a simple framework linking waste management, nutrient cycling, biodiversity, and new business opportunities; and third, to examine current policies to identify barriers to broader IBOWM adoption. Together, these objectives underscore IBOWM's potential to enhance sustainability and food security in rapidly urbanizing regions.

2 Environmental, resource recovery, and biodiversity and ecosystem health benefits

Integrating IBOWM into waste management and agricultural systems not only dramatically reduces landfill waste and greenhouse gas emissions but also reinforces the circular economy by transforming organic waste into valuable by-products. Additionally, this integration enhances ecosystem health and maintains biodiversity, showcasing IBOWM's transformative potential as a sustainable solution for today's environmental and economic challenges. Figure 1 encapsulates these diverse and highly interrelated benefits, illustrating IBOWM's critical role in promoting environmental sustainability, resource recovery, and biodiversity enhancement.

2.1 Environmental benefits

IBOWM redirects organic residues such as food scraps and agricultural by-products from landfills into insect bioconversion systems, significantly cutting methane emissions under the anaerobic conditions that drive climate change (Noudeng et al., 2018; Singh

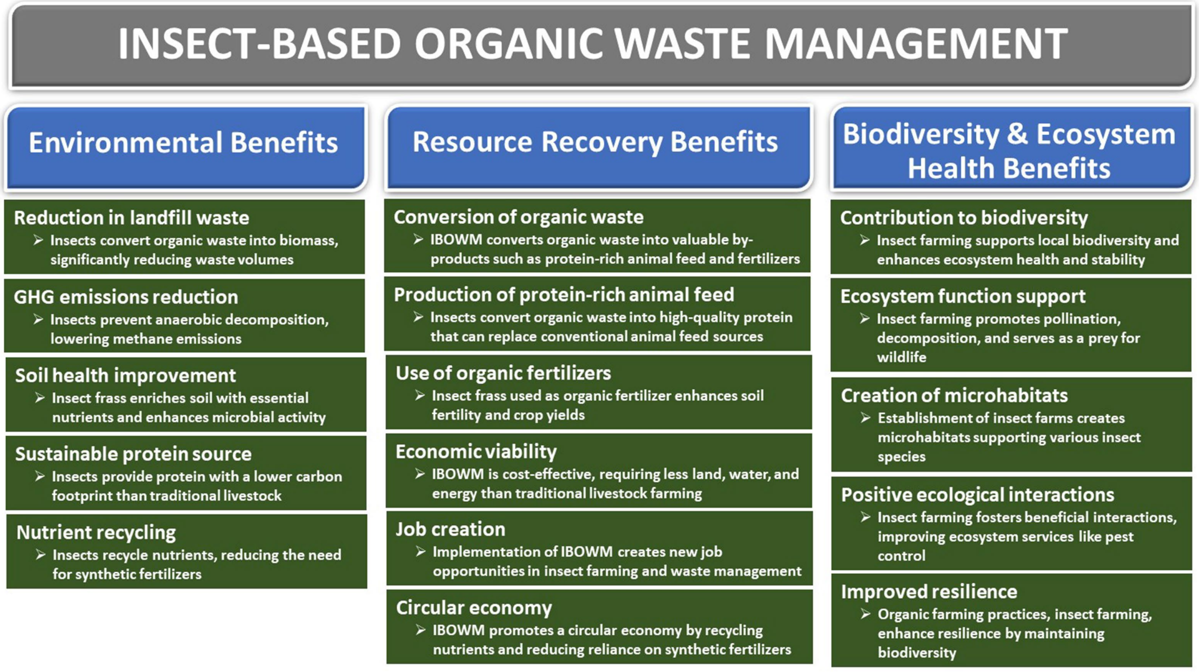

FIGURE 1
Environmental, resource recovery, and biodiversity benefits of IBOWM.

et al., 2019). By harnessing black soldier fly larvae, IBOWM not only mitigates greenhouse gases but also shifts waste disposal away from unsustainable practices linked to rising emissions (Diener et al., 2011; Gligorescu et al., 2020). The nutrient-rich frass and larval biomass produced enhance soil fertility and ecosystem health, embodying circular-economy principles through efficient resource recovery (Czekała et al., 2020; Pliantiangtam et al., 2021). Empirical case studies reveal bioconversion efficiencies up to 45.9% and demonstrate the approach's scalability across both agricultural operations and urban waste streams (Surendra et al., 2020; Broeckx et al., 2021).

2.1.1 Reduction in landfill waste

Insect-based organic waste management (IBOWM) offers a promising approach to reduce the amount of organic waste sent to landfills, addressing a central challenge in contemporary waste management. Traditional methods such as landfilling tend to accumulate organic residues, whereas employing insects, particularly BSF larvae, can effectively convert organic waste into high-value biomass (Scharff et al., 2023). For example, Rekha et al. (2022) demonstrated that BSF larvae achieved a waste reduction efficiency of 73.8% when processing municipal organic waste, underscoring the superior efficacy of this approach compared to conventional disposal practices.

Further evidence of IBOWM's effectiveness is provided by various case studies. During a pilot project in Thailand, Usapein and Chavalparit (2014) reported that using BSF larvae for food waste treatment diverted nearly 79% of organic waste from landfills over a two-year period. Raga and Cossu (2017) also noted that such waste diversion significantly mitigates secondary environmental problems, including leachate contamination and the exacerbation of greenhouse gas emissions. Additionally, research by Kim et al. (2021) indicates that insects are highly adaptable, thriving on diverse organic substrates like food scraps and agricultural by-products, thereby enhancing overall waste processing efficiency. In contrast to traditional approaches, where, for example, approximately 90% of South Africa's 55 million tonnes of general waste was landfilled in 2017, IBOWM not only lowers landfill volumes but also promotes a circular economy by recycling nutrients and producing high-value outputs such as animal feed and organic fertilizers (Ojha et al., 2020; Olatayo et al., 2024).

2.1.2 Greenhouse gas emissions reduction

IBOWM substantially curbs GHG emissions by diverting biodegradable material from anaerobic landfills, where it would decompose into methane, a gas with roughly 25 times the 100-year global warming potential of CO_2 to insect bioconversion systems (Chen et al., 2023). Rearing BSF larvae on food and agricultural residues shrinks the pool of substrate available for methanogenesis, with Chineme and Assefa (2023) reporting up to an 80% cut in methane emissions compared to traditional waste disposal or composting methods.

Beyond waste diversion, BSF larvae biomass serves as a low-carbon alternative to conventional feed proteins. Ellawidana et al. (2023) showed that replacing standard broiler feeds with full-fat BSF larvae meal enhances feed conversion efficiency and closes the organic-waste loop, thereby reducing overall methane emissions linked to both feed manufacture and post-farm waste decomposition. Fukuda et al. (2022) demonstrated that supplementing beef steers' low-quality forage with BSF larvae improves nutrient intake and feed conversion ratios, and also lowers CO_2-equivalent emissions per kilogram of beef. In aquaculture, Priyadarshana et al. (2022) found that including BSF larvae in fish diets boosts growth performance and gut-microbiota health, which can reduce antibiotic reliance and associated pollutant runoff.

Life-cycle assessments underscore the climate advantage of insect protein: BSF larvae production emits roughly 1.5 kg CO_2-equivalent per kilogram of protein versus about 10 kg for beef (Huis and Oonincx, 2017). Moreover, by valorizing organic waste into insect biomass, IBOWM decreases dependence on synthetic fertilizers, significant sources of nitrous oxide and CO_2 during their synthesis and field application (Lisboa et al., 2024). A Dutch pilot study reported a 70% reduction in methane emissions when BSF larvae processed food waste instead of conventional composting (Chineme and Assefa, 2023), and European Union waste-management directives are increasingly recognizing insect farming as a high-impact strategy for meeting GHG reduction targets (Al-Shatnawi et al., 2020).

2.1.3 Soil health improvement

Frass, a by-product composed of insect excreta, leftover substrate, and fragments of exoskeleton, is a powerful enhancer of soil fertility and overall health. Rich in nitrogen, phosphorus, and potassium, it functions as a potent organic fertilizer that supports robust nutrient availability in soils (Amorim et al., 2024). Beyond its nutrient content, frass promotes microbial diversity and abundance essential for sustaining soil fertility. Research on BSF frass shows that its application can significantly enhance nitrogen mineralization and nutrient release, thereby improving soil structure, nutrient cycling, water retention, and pathogen suppression (Beesigamukama et al., 2021).

Field trials further underscore the impact of frass on crop productivity. For example, in Uganda, maize treated with BSF frass achieved yield increases of up to 30% compared to those using conventional fertilization (Beesigamukama et al., 2022), while studies in sub-Saharan Africa indicate that edible insect frass enhances both the yield and nutritional quality of crops such as tomatoes, kales, and cowpeas (Anyega et al., 2021). Moreover, incorporating insect frass into agricultural practices aligns with circular economy principles by recycling organic waste and reducing reliance on synthetic fertilizers. This strategy not only minimizes problems like nutrient runoff and soil degradation but also strengthens the resilience of agricultural systems to climate variability (Nyamwasa et al., 2020; Poveda, 2021). Table 1 summarizes these environmental benefits, highlighting the key mechanisms through which IBOWM contributes to sustainable waste management solutions.

2.2 Resource recovery

IBOWM converts up to 90% of food-waste biomass into protein-rich larvae and nutrient-dense frass, yielding high-value animal feed and organic fertilizers (Bosch et al., 2019; Ţucă and Stan, 2023). By integrating BSF and mealworm bioconversion, this circular-economy approach slashes landfill volumes while delivering environmental and economic gains, high feed-conversion ratios, reduced disposal costs, and closed nutrient loops that reintegrate energy and matter into agricultural systems (Huis and Oonincx, 2017; Madau et al., 2020; Wang and Shelomi, 2017).

Yet IBOWM must address contaminant risks inherent in feedstocks. Agricultural and industrial residues often contain persistent heavy metals, lead, mercury, cadmium, that can accumulate in frass and, if unmanaged, contaminate soils and water bodies (Oluwatoyin, 2018). Likewise, antibiotic residues from livestock manure and sewage sludge promote the spread of antibiotic-resistance genes (ARGs); although insect bioconversion can reduce ARG abundance, conventional treatments rarely eliminate them completely, posing ecological and human-health concerns (Deng et al., 2022; Thakali et al., 2020). Furthermore, co-selection by metals and antibiotics may drive microbial communities to harbor both metal- and drug-resistance traits, amplifying the potential dissemination of resistance genes throughout agroecosystems (Pepper et al., 2018; Kanger et al., 2020).

2.2.1 Conversion of organic waste to valuable by-products

IBOWM provides a sustainable strategy for transforming organic waste into high-value commodities. By employing substrates such as food scraps and agricultural residues for rearing insect larvae, including BSF and oil palm weevils, the process not only diverts substantial waste from landfills but also produces high-quality protein. For example, Chamoun et al. (2023) demonstrated that protein derived from this process can effectively substitute conventional

TABLE 1 Summary of the environmental benefits of IBOWM.

Benefit	Mechanism	Supporting evidence
Reduction in landfill waste	BSF larvae convert approximately 73.8% of municipal organic waste into biomass, diverting it from anaerobic landfills	Rekha et al. (2022)
Greenhouse gas emissions reduction	Diverting organic waste to BSF bioconversion cuts methane emissions by up to 80%; BSFL protein emits ~1.5 kg CO_2-e/kg versus ~10 kg CO_2-e/kg for beef	Chineme and Assefa (2023); Huis and Oonincx (2017)
Soil health improvement	Frass—rich in N, P, and K—enhances soil structure, nutrient cycling, water retention, and microbial diversity, boosting crop yields by up to 30%	Beesigamukama et al. (2021); Beesigamukama et al. (2022)
Sustainable protein source	BSFL meal provides an efficient, low-carbon protein for poultry, cattle, and fish, improving feed conversion and reducing demand on land- and water-intensive crops	Ellawidana et al. (2023); Fukuda et al. (2022); Priyadarshana et al. (2022)
Nutrient recycling	Converting waste into larvae and frass recycles valuable nutrients, decreasing reliance on synthetic fertilizers and lowering associated nitrous-oxide and CO_2 emissions	Nyamwasa et al. (2020); Lisboa et al. (2024)

TABLE 2 Summary of resource recovery and circular economy benefits of IBOWM.

Key benefit	Description	Examples
Conversion of organic waste	IBOWM transforms organic waste into high-value products such as protein-enriched animal feed and organic fertilizers, diverting waste from conventional disposal methods.	Using BSF larvae to process food waste into insect protein (Munubi and Lamtane, 2021).
Production of protein-rich animal feed	By converting organic waste, insects yield high-quality protein that can serve as a sustainable alternative to traditional animal feed sources.	Insect meal with 60–70% crude protein content (Urra et al., 2019).
Use of organic fertilizers	Insect-derived frass, rich in essential nutrients, enhances soil fertility and boosts crop yields when used as an organic fertilizer.	BSF frass leading to a 30% increase in maize yield (Carnier et al., 2019).
Economic viability	IBOWM is cost-effective, needing significantly less land, water, and energy than conventional livestock farming, which lowers overall production costs.	Achieving feed conversion ratios as low as 1.7 (Siregar et al., 2023).
Job creation	The application of IBOWM stimulates local economies by creating employment opportunities in sectors such as insect rearing, processing, and waste management.	New job opportunities emerging in local insect farming operations (Sousa et al., 2021).
Circular economy	By recycling nutrients and reducing reliance on synthetic fertilizers, IBOWM supports a circular economy model that enhances sustainability and resource efficiency.	Small and medium-sized enterprises focused on waste valorization through insect production (Головина et al., 2023).

animal feed. Previously, Gasco et al. (2020) highlighted that this bioconversion significantly reduces the environmental footprint of traditional feedstocks, while Moqsud (2021) noted the superior feed conversion efficiency achieved through insect biomass production.

In addition to protein production, insect by-products such as frass serve as exceptional organic fertilizers. Frass, rich in nitrogen, phosphorus, and potassium, enhances soil health by increasing microbial diversity and promoting nutrient cycling, as reported by Voltolini et al. (2020). Its application has also been linked to improved crop yields; for instance, Carnier et al. (2019) recorded a 30% increase in maize yield in Uganda with BSF frass, and Munubi and Lamtane (2021) found that processing food waste with BSF larvae in the Netherlands produced around 20,000 tons of insect protein annually. Collectively, these findings emphasize that IBOWM not only recycles waste into valuable resources but also bolsters the circular economy and enhances environmental sustainability.

2.2.2 Economic implications

Insect-based organic waste management (IBOWM) delivers notable economic advantages by converting organic waste into high-value commodities such as protein-rich animal feed and organic fertilizers at a lower cost than conventional methods. Insect protein production is particularly efficient, requiring significantly less land, water, and energy than traditional livestock farming. Chiaraluce et al. (2021) report that this approach is highly resource-efficient, and Siregar et al. (2023) highlight that insects can achieve a feed conversion ratio as low as 1.7 compared to around 8 for cattle. This improved efficiency not only reduces operational expenses for farmers and businesses but also boosts the overall economic viability of IBOWM systems.

Moreover, IBOWM has the potential to stimulate local economies by generating opportunities across waste management, insect farming, and agricultural sectors. As the demand for sustainable protein and organic fertilizers grows, the market is well positioned for expansion and job creation in areas such as insect rearing, processing, and distribution (Sousa et al., 2021). The circular economy model inherent in IBOWM further promotes collaboration among farmers, waste management firms, and food producers, spurring innovation and economic diversification (Trică et al., 2019). For instance, in Indonesia, the adoption of circular economy principles in insect farming has led to the emergence of numerous small and medium-sized enterprises focused on waste valorization (Головина et al., 2023), while similar initiatives in Europe have successfully cut waste disposal costs and increased revenue from insect-based products (Goyal et al., 2016). These findings, summarized in Table 2, underscore IBOWM's transformative potential to drive growth, create employment opportunities, and support a more resilient, circular economy.

2.3 Biodiversity and ecosystem health

IBOWM enhances biodiversity and ecosystem health by embedding insect farming within agricultural landscapes, creating microhabitats that sustain diverse insect populations and robust pollinator communities (Kovács-Hostyánszki et al., 2017). By fostering interactions among native flora and fauna, IBOWM boosts essential ecosystem services such as nutrient cycling and biological pest control that underpin sustainable crop production (Garratt et al., 2018; Sutter and Albrecht, 2016). Field studies show that IBOWM systems with ecological margins and varied cropping practices deliver higher species richness and improved landscape connectivity for pollinators (Dilts et al., 2023; Mbelede et al., 2023). Overall, by marrying waste management with biodiversity conservation, IBOWM fortifies ecosystem resilience and offers a sustainable pathway for agricultural systems (Jankielsohn, 2018; Prajapati et al., 2024).

2.3.1 Contribution to biodiversity

Insect farming enhances local biodiversity by transforming organic waste into substrates that support a wide variety of insect species, thereby increasing habitat complexity and contributing to a more resilient agricultural landscape (Paradise et al., 2014). Integrated with organic farming practices, this approach has been shown to boost species richness and abundance, as evidenced by studies in bottle gourd cultivation where insect diversity was significantly elevated (Prajapati et al., 2024). Moreover, the presence of diverse insect communities is critical for sustaining essential ecosystem functions. These communities not only enhance pollination and expedite the decomposition of organic matter but also serve as an important food source for wildlife (Adjaloo and Oduro, 2013). Additionally, robust insect populations help reduce ecosystem vulnerability to pests and diseases (Kremen and Miles, 2012) while promoting improved nutrient cycling and pest regulation, thereby reinforcing overall ecosystem stability and agricultural productivity (Froidevaux et al., 2017).

2.3.2 Ecological interactions

Insect farming integrates seamlessly into agricultural landscapes, fostering beneficial ecological interactions that enhance ecosystem health and stability. By converting organic waste into substrates that support diverse insect communities, this approach not only boosts overall biodiversity but also reinforces essential ecosystem services such as pollination and pest control. Research by Lichtenberg et al. (2017) indicates that diverse insect populations build resilience against environmental stressors and stabilize ecosystem processes, while cultivating insects alongside crops creates complex microhabitats that support various arthropods critical for nutrient cycling and pest regulation (Estrada-Carmona et al., 2022).

Moreover, insect farming has a pronounced positive impact on local pollinator populations. Studies have shown that organic farming practices incorporating insect rearing promote higher diversity and abundance among pollinators like bees and butterflies (Stein-Bachinger et al., 2020), with Boonchuay and Bumrungsri (2022) documenting elevated bat activity, closely linked to insect abundance, in organic rice fields compared to conventional ones. Reviews and meta-analyses further suggest that agricultural systems characterized by reduced pesticide use and increased habitat complexity support enhanced species richness and biodiversity, thereby reinforcing sustainable agriculture (Estrada-Carmona et al., 2022). These findings, along with additional supporting evidence, are summarized in Table 3, which details the key ecological benefits of IBOWM and highlights its transformative role in promoting biodiversity and ecosystem health.

3 Framework and metrics for enhancing ecosystem services through IBOWM

This section presents a framework and metrics for enhancing ecosystem services through IBOWM by turning organic waste into valuable insect-derived products while fostering environmental, economic, and social sustainability. It builds on the principle of ecosystem multifunctionality, stressing that biodiversity restoration is essential for resilient service delivery (Allan et al., 2015). The framework integrates supportive regulations, stakeholder engagement, and targeted incentives to embed IBOWM across varied socio-ecological contexts (Keeler et al., 2019). It employs metrics such as water-quality to human-well-being indices and payment-for-ecosystem-services schemes to inform land-use decisions and promote sustainable practices (Keeler et al., 2012). Spatial modeling of land-use changes and service distributions guides adaptive management at multiple scales (Liu et al., 2023; Bagstad et al., 2014), and continuous feedback loops ensure the framework evolves with new ecological insights, addressing trade-offs and synergies for long-term ecosystem health (Bravo et al., 2023; Hanes et al., 2017; Ringold et al., 2013).

3.1 Framework for enhancing ecosystem services through IBOWM

The IBOWM framework adopts a comprehensive strategy that integrates environmental, economic, and social benefits by harnessing the natural abilities of insects, specifically BSF and oil palm weevil larvae, to transform organic waste into valuable by-products. This innovative process drastically reduces waste sent to landfills, mitigates greenhouse gas emissions such as methane and carbon dioxide, and recycles important nutrients back into agricultural systems. The recovered biomass is repurposed as animal feed, while the resulting frass functions as a nutrient-rich organic fertilizer (Allan et al., 2015), as depicted in Figure 1.

Beyond waste reduction, insect farming plays a pivotal role in enhancing local biodiversity by creating microhabitats that support beneficial insects, including pollinators and natural pest predators, thereby stabilizing key ecosystem processes (Nelson et al., 2010). Economically, the establishment of insect farming operations drives local growth by generating employment opportunities in waste management and agriculture, and bolstering food security through alternative protein sources (Gittman et al., 2016). Importantly, by diverting organic waste

TABLE 3 Summary of the biodiversity and ecosystem health benefits of IBOWM.

Key benefit	Description	Examples
Enhanced biodiversity	Insect farming enriches local biodiversity, thereby promoting ecosystem stability and overall health.	Organic bottle gourd cultivation practices that boost insect diversity (Prajapati et al., 2024).
Support for ecosystem functions	This approach bolsters crucial ecosystem functions, from pollination and decomposition to serving as prey for wildlife.	Diverse insect communities significantly enhance pollination services (Adjaloo and Oduro, 2013).
Formation of microhabitats	The development of insect farms creates varied microhabitats that support numerous insect species and promote nutrient cycling.	Agricultural practices that foster nutrient cycling through microhabitat creation (Froidevaux et al., 2017).
Enhanced ecological interactions	Insect farming encourages beneficial ecological interactions that improve services such as pest control and natural predation.	Increased bat activity linked to higher insect abundance in organic rice fields (Boonchuay and Bumrungsri, 2022).
Augmented resilience	Integrating insect farming within organic agriculture boosts ecosystem resilience by sustaining biodiversity and stability.	Meta-analyses indicating greater biodiversity and resilience in complex agricultural landscapes (Estrada-Carmona et al., 2022).

and repurposing it into food, feed, and fertilizer, IBOWM contributes to climate change mitigation by reducing the carbon footprint relative to conventional waste management and livestock production (Platonova et al., 2022). Figure 2 summarizes these interconnected benefits, illustrating how IBOWM offers a transformative solution to both environmental and economic challenges while paving the way for a more sustainable and resilient future.

3.2 Implementation of the framework

Effective implementation of the IBOWM framework begins with targeted educational campaigns, participatory initiatives, and mass-media outreach to showcase its environmental and nutritional benefits (Hunter et al., 2023) as depicted in Figure 3. Engaging local communities from the outset fosters ownership and ensures stakeholder input guides the integration of IBOWM into existing waste management and agricultural practices (Bozdaglar, 2023). At the same time, co-developing harmonized regulatory frameworks with government bodies, researchers, and industry partners establishes the safety, quality-control, and sustainability standards needed, drawing lessons from the EU's environmental management models (Duc and Thanh, 2023). Aligning IBOWM with current waste systems then creates synergies that drive sustainable farming, stimulate local economies, and generate new jobs in waste management and insect production (Juniyanti et al., 2024). Finally, ongoing research coupled with targeted economic incentives and clear performance metrics enables adaptive monitoring and continuous improvement, maximizing the framework's environmental, economic, and social impacts (Puiu and Udriştioiu, 2023). Table 4 outlines the essential steps and key considerations for successfully implementing the framework for enhancing ecosystem services through IBOWM.

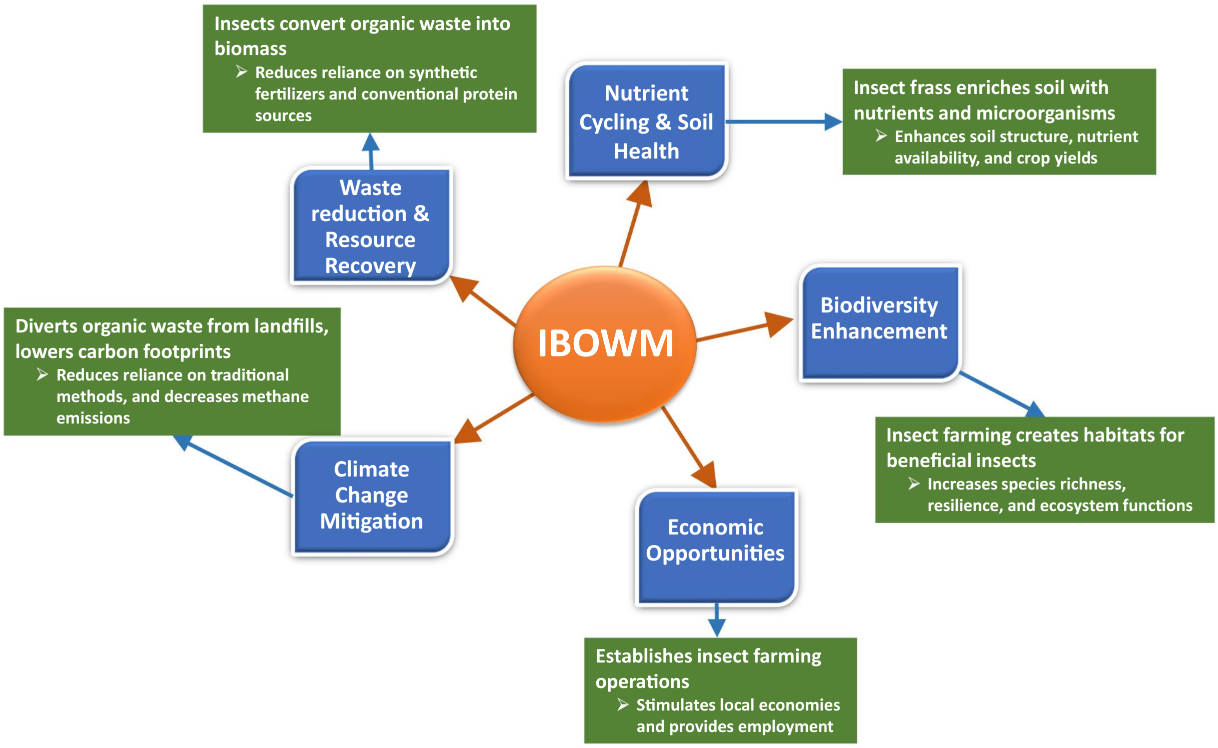

FIGURE 2
Framework for enhancing ecosystem services through IBOWM.

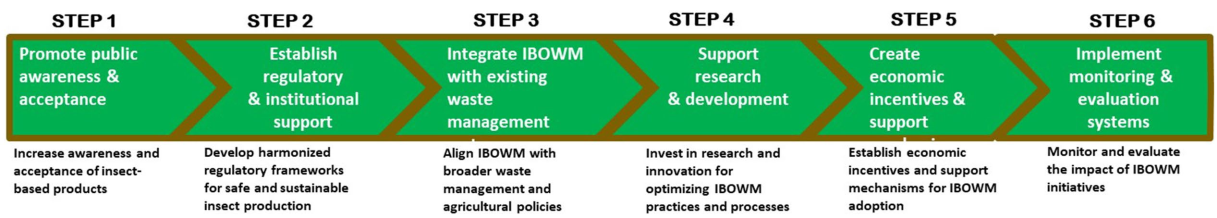

FIGURE 3
Essential steps and their description for the successful implementation of IBOWM.

TABLE 4 Essential steps for the successful implementation of IBOWM.

Step	Key considerations
1	Public education campaigns, targeted educational programs, community engagement initiatives, and mass media campaigns. Address cultural perceptions and provide evidence-based information about safety and efficacy. Involve local communities in IBOWM implementation.
2	Collaboration between policymakers, industry stakeholders, researchers, and regulatory bodies. Emphasize safety, quality control, and environmental sustainability. Learn from successful regulatory models (e.g., European Union). Provide resources, training, and technical assistance to insect farmers.
3	Recognize IBOWM as a viable method for reducing organic waste. Promote the use of organic waste as feed for insect production. Support local economies and create synergies with other sustainable agricultural practices. Collaborate between waste management authorities, agricultural sectors, and insect farming industries.
4	Governments and funding agencies to support research initiatives. Collaborative research between universities, research institutions, and industry stakeholders. Develop new technologies and methodologies. Conduct lifecycle assessments and document economic and ecological benefits to support policy decisions.
5	Financial incentives, grants, and subsidies to lower initial investment barriers. Provide technical assistance, training programs, and access to markets. Foster economic resilience and create new job opportunities, especially in rural communities. Contribute to sustainable livelihoods and enhanced food security.
6	Implement metrics and indicators to assess effectiveness in achieving waste reduction, enhancing soil health, promoting biodiversity, and creating economic opportunities. Continuous evaluation to provide insights into current policies and identify areas for improvement. Ensure IBOWM practices adapt to changing circumstances and stakeholder needs for long-term sustainability.

3.3 Evaluating IBOWM impact: metrics and indicators

A robust evaluation of IBOWM's impact on ecosystem services hinges on a suite of metrics spanning environmental, economic, and social domains (Allan et al., 2015; Balvanera et al., 2006). Waste reduction and resource recovery are gauged by the volume of organics diverted from landfills, declines in methane emissions, and the share of nutrients returned to fields via insect biomass and frass, metrics shown to correlate with substantial GHG abatements (Fu et al., 2015; Ma et al., 2016). Nutrient cycling and soil health are tracked through changes in fertility indicators, crop-yield boosts from frass applications, and improvements in soil structure and microbial activity (Ouyang et al., 2020). Biodiversity enhancement is assessed by monitoring gains in species richness and habitat complexity following IBOWM adoption (Allan et al., 2015; Balvanera et al., 2006; Egoh et al., 2009). Economic outcomes, job creation, income growth, and market expansion for insect-derived products provide insight into the model's viability (Maseyk et al., 2017; Zhao and Wang, 2021). Climate-change mitigation benefits are measured via net reductions in greenhouse-gas emissions and overall carbon footprints (Martín-López et al., 2012; Guerry et al., 2015). Finally, public awareness and acceptance, key to scaling IBOWM are evaluated through surveys of consumer knowledge and practice uptake (Keeler et al., 2019). Table 5 offers an in-depth overview of these measures and serves as a practical guide for assessing IBOWM's success and impact.

4 Best practices and challenges in implementing IBOWM

Effective IBOWM implementation hinges on embedding systems into local economies through government-led training and strong public-private-community partnerships to drive participation and ownership (Khairifa et al., 2025; Dibia et al., 2022). Overcoming regulatory and market hurdles requires aligning local regulations with national policies, clarifying roles within informal waste sectors, and adopting life-cycle assessment tools for informed decision-making (Avarand et al., 2023; Ebrahimi and North, 2017). Boosting public awareness via targeted education programs increases uptake, while ensuring social equity in outreach protects vulnerable communities from being left behind (Knickmeyer, 2020; Sarkodie and Owusu, 2020). Finally, sustaining long-term success demands continuous R&D, leveraging multi-criteria decision frameworks, digital sorting technologies, and advanced composting or recycling innovations to keep IBOWM adaptable, efficient, and scalable (Alsubaei et al., 2022; Jayasinghe et al., 2023; Sadessa and Balo, 2025).

4.1 Lessons learned and best practices

Implementing IBOWM across diverse regions has provided valuable insights and highlighted best practices essential for future endeavors. Integrating insect farming into local economies has proven particularly effective. For example, in Thailand, cricket farming not only supplies a sustainable protein source but also fosters social cohesion among farmers by reinforcing strong institutional support and cooperative frameworks (Halloran et al., 2016a). Similarly, in Africa, using local agricultural by-products as feed has effectively reduced waste and enhanced sustainability, demonstrating that leveraging local resources can lower costs and strengthen insect farming operations (Alemu et al., 2023). Additionally, targeted agricultural training and nutrition education have played key roles in promoting insect farming, thereby addressing food security while driving economic development.

In the European Union, the valorization of organic waste streams for insect farming underscores the need to overcome regulatory and market challenges. Supportive policy frameworks and market incentives have been instrumental in encouraging the use of organic waste in insect farming and in creating opportunities for insect-based products (Peer et al., 2021). Continuous research and innovation are vital; collaborations between research institutions, governments, and industry stakeholders have facilitated the development of new technologies and optimized processes for more efficient operations (Fowles and Nansen, 2019). Equally important, public awareness

TABLE 5 Sustainability metrics and indicators for assessing IBOWM implementation.

Sustainability dimension	Metric	Indicator/measurement
Waste reduction and resource recovery	Volume of organic waste diverted	Total organic waste diverted from landfills to insect farming operations (Tons, metric tons)
	Reduction in landfill methane emissions	Decrease in methane emissions from landfills due to waste diversion (Tons $CO_{2\text{-equivalent}}$, tCO_{2e})
	Nutrient recycling rate	Percentage of nutrients recycled into agricultural systems via insect biomass and frass (%)
Nutrient cycling and soil health	Soil fertility improvement	Changes in soil nutrient content and organic matter (mg/L)
	Crop yield enhancement	Increase in crop yields resulting from the application of insect frass as organic fertilizer (kg/ha)
	Soil health indicators	Improvements in soil structure, microbial activity (e.g., colony-forming units [CFU]), and water-holding capacity (%)
Biodiversity enhancement	Species richness and abundance	Increase in the number and abundance of beneficial insect species in agricultural landscapes (Number of species, Individuals per square meter)
	Habitat diversity	Diversity and complexity of habitats created by insect farming (Habitat diversity index, Number of habitat types)
	Ecosystem resilience	Ability of ecosystems to recover from stressors such as pest outbreaks and climate variability (e.g., recovery time, resilience index)
Economic opportunities	Job creation	Number of jobs generated in insect farming, waste management, and agricultural sectors (Number of jobs)
	Income generation	Income generated by insect farming operations and its impact on local economies (Currency, e.g., USD)
	Market development	Growth and development of markets for insect-based products (Market size in currency, e.g., USD)
Climate change mitigation	Greenhouse gas emissions reduction	Reduction in greenhouse gas emissions achieved through IBOWM practices (Tons $CO_{2\text{-equivalent}}$, tCO_{2e})
	Carbon footprint	Overall carbon footprint of insect farming compared with traditional methods (Tons $CO_{2\text{-equivalent}}$, tCO_{2e})
	Renewable resource utilization	Use of renewable resources and reduced reliance on synthetic fertilizers and conventional livestock feed (%)
Public awareness and acceptance	Consumer awareness	Level of consumer understanding about the benefits of insect-based products (Survey scores, e.g., Likert scale)
	Public acceptance	Adoption rate of insect-based products among consumers and stakeholders (Adoption rate in %)
	Educational outreach	Effectiveness of public education campaigns and community engagement initiatives (Number of events, Participants)

initiatives such as educational campaigns and community engagement have successfully promoted the benefits of insect farming and addressed cultural misconceptions by providing evidence-based information on the safety and nutritional value of insect-based products (Alemu et al., 2023).

Furthermore, ensuring the long-term sustainability of IBOWM initiatives depends on addressing both environmental and social impacts. Best practices include conducting thorough environmental impact assessments, upholding fair labor standards, and ensuring that insect farming operations do not harm local ecosystems (Pliantiangtam et al., 2021). Projects that prioritize social equity and environmental protection tend to achieve long-term success and contribute significantly to sustainable development goals. By integrating these insights and practices, future IBOWM initiatives can enhance agricultural resilience and help create a more sustainable and resilient food system. Table 6 summarizes these key lessons and best practices, offering practical strategies and examples to guide upcoming IBOWM projects.

4.2 Overcoming key implementation challenges in IBOWM

IBOWM faces several key hurdles that impede its widespread adoption. A major challenge is the existing regulatory framework; many regions continue to use food safety and animal feed regulations that do not address the unique aspects of insect production, creating uncertainty for producers and investors (Broeckx et al., 2021). Limited public awareness and acceptance of insects as a viable food source further constrain market demand. Additionally, scaling up insect farming operations to meet larger market needs requires significant investments in infrastructure, advanced technology, and workforce training, while the inconsistent availability of organic waste as feed adds to production variability and impacts product quality (Fowles and Nansen, 2019; Pazmiño et al., 2023).

To overcome these challenges, several innovative solutions are emerging. Establishing clear, targeted regulatory frameworks is vital; comprehensive guidelines can ensure food safety, improve

TABLE 6 Summary of lessons learned and best practices in IBOWM.

Key area	Description	Examples
Integration with local economies	Emphasizes the importance of embedding insect farming within local economic activities.	Cricket farming initiatives in Thailand have strengthened social cohesion (Halloran et al., 2016a).
Leveraging Local Resources	Focuses on using locally available agricultural by-products as feed for insect production.	Utilizing indigenous agricultural residues in Africa to cut production costs (Alemu et al., 2023).
Addressing regulatory challenges	Highlights the need for clear regulatory frameworks that support safe and sustainable insect farming.	European Union regulations now facilitate the incorporation of insects into animal feed (Badu-Yeboah et al., 2018).
Promoting research and innovation	Stresses continuous research and collaborative initiatives to optimize production processes and efficiency.	Partnerships between research institutions and industry players contribute to better practices (Fowles and Nansen, 2019).
Enhancing public awareness	Recommends educational campaigns aimed at boosting public understanding and acceptance of insect farming.	Community engagement programs have been instrumental in changing perceptions (Alemu et al., 2023).
Ensuring environmental and social sustainability	Encourages conducting environmental impact assessments and promoting fair labor practices alongside sustainability goals.	Projects that focus on social equity and environmental protection serve as robust models (Pliantiangtam et al., 2021).

TABLE 7 Overview of challenges and proposed solutions in IBOWM.

Key challenge	Description	Proposed solution
Regulatory environment	Inadequate food safety and animal feed regulations create uncertainty in insect farming.	Develop and implement clear regulatory frameworks (Badu-Yeboah et al., 2018).
Public awareness and acceptance	Limited public awareness and acceptance hinder the recognition of insects as a viable food source.	Launch targeted public education campaigns (Al-Rumaihi et al., 2020).
Scalability of operations	Scaling production to meet market demand poses significant challenges.	Invest in infrastructure, technology, and workforce training (Pazmiño et al., 2023).
Sourcing organic waste	Inconsistent availability of organic waste disrupts the feed supply for insects.	Establish reliable supply chains for organic waste (Fowles and Nansen, 2019).
Technological advancements	Enhanced efficiency and scalability require further technological innovation.	Adopt automated insect farming systems (Banks et al., 2013).

market confidence, and market incentives can further stimulate industry growth (Badu-Yeboah et al., 2018; Pinotti and Ottoboni, 2021). Public education campaigns are also essential to dispel myths and highlight the environmental and nutritional benefits of insect-based products (Al-Rumaihi et al., 2020; Candian et al., 2023). Additionally, technological advancements, such as implementing automated insect farming systems and enhanced waste processing methods, promise to improve efficiency and scalability. Integrating insect farming with existing agricultural practices may also create beneficial synergies that bolster both waste management and crop production (Al-Otaibi et al., 2022; Azizah et al., 2021). Table 7 provides an overview of the key challenges and the proposed strategies to overcome them.

4.3 Global perspectives on circular bio-waste management

The United Nations Environment Program's Global Waste Management Outlook 2024 underscores how inadequate disposal exacerbates climate change, biodiversity loss and public-health risks, challenges most acute in low- and middle-income countries where open dumping and burning remain widespread (UNEP, 2024; Ferronato and Torretta, 2019). This report projects a sharp rise in municipal solid waste and champions a circular-economy shift, turning refuse into resources which dovetails perfectly with insect-driven bioconversion strategies.

In Europe, pilot programs and policy frameworks have pioneered integrated biowaste solutions that combine enhanced source separation, advanced composting and novel valorization pathways. Sharma et al. (2021) document how circular-economy principles boost recovery rates, while the Biocircularities project catalogues 36 exemplary practices, ranging from decentralized collection hubs to high-efficiency digesters that cut landfill dependence and reclaim valuable nutrients (Johari et al., 2021). Concurrently, UNECE analyses highlight that municipalities can leverage recycling, waste-to-energy and bioconversion to transform burgeoning waste streams into economic and environmental assets (Sharma et al., 2021).

Beyond policy, technology and community engagement are catalyzing change. The World Bank warns that without modern systems, waste management will continue to drive greenhouse-gas emissions and economic losses in urban centers worldwide (Islam et al., 2025). Mobile apps and sensor-based sorting tools are already empowering households to reduce and segregate food waste, laying the groundwork for scalable insect-rearing operations (Hong et al., 2023). At the same time, linking IBOWM to the UN Sustainable Development Goals clarifies its contributions to zero hunger, clean water, climate action and sustainable cities (Sharma et al., 2021).

Finally, regional success stories, such as the collaborative waste-reduction initiative on the Mississippi Gulf Coast demonstrate how multi-stakeholder platforms can optimize diversion, recovery and local buy-in (Evans-Cowley and Arroyo-Rodríguez, 2013). These global lessons reinforce the urgency of sustainable waste governance and spotlight insect-based bioconversion as a keystone technology in a truly circular, regenerative bio-economy.

5 Enhancing policy frameworks, strategies, and future directions for IBOWM

Integrating IBOWM into current policy frameworks is key to boosting environmental sustainability and food security in line with the UN SDGs (Béné et al., 2022; Kremen, 2020). Existing regulations often link food systems and ecological health but lack a holistic sustainability focus, ignoring ecological intensification and community engagement (Akimova and Коваленко, 2021; Diachkova et al., 2022). Robust policies should embed participatory governance, incentivize agricultural innovation, including digital tools, and expand education and training to empower stakeholders (Comerford et al., 2021; MacPherson et al., 2022; Pretorius and Schönfeldt, 2023). Clear sustainability metrics and regulatory incentives will guide implementation and accountability across diverse contexts (Allen et al., 2018; Zou et al., 2023). Finally, future research must refine urban food-system frameworks, deepen interdisciplinary collaboration, and apply participatory modeling to scale IBOWM effectively (Kapsdorferova et al., 2021; Tahat et al., 2020). Iterative alignment of policy, practice, and evidence will unlock IBOWM's potential to transform waste management and strengthen food-system resilience.

5.1 Current policies and regulations

Policies supporting IBOWM are increasingly being designed to integrate insect farming into sustainable food systems and waste management practices. For instance, in the European Union, the Animal Feed Regulation (EU Regulation 2017/1017) has established a framework for the safe incorporation of insect-derived products into animal feed, positioning insects as a sustainable alternative protein source under rigorous food safety standards (Rhoades et al., 2019). Similarly, Thailand has implemented comprehensive guidelines that emphasize rearing insects on organic waste and producing safe insect-based products, thereby reinforcing best practices for sustainable insect farming (Shahrani and Al–Surimi, 2018).

Despite these advances, the industry continues to face significant regulatory challenges. A major issue is the lack of harmonized regulations across regions, which not only creates trade barriers but also complicates market access for insect-based products. Furthermore, many current agricultural and waste management policies fail to address the unique operational needs of insect farms, leading to compliance uncertainties and inefficiencies (Wang et al., 2019). In addition, persistent public misconceptions regarding the safety and nutritional value of insect products further constrain consumer acceptance and market demand (Schmidt et al., 2018). Overcoming these obstacles will require policymakers to develop coherent, harmonized regulations that ensure safety and quality, enhance public trust, and support the growth of the industry. Table 8 provides a summary of these current policies and regulatory challenges, offering a detailed overview of established frameworks, existing issues, and the influential role of public perception in advancing IBOWM.

5.2 Recommendations for policy enhancement

Promoting the widespread adoption of IBOWM begins with robust support for industrial-scale production and clear regulatory oversight. Governments should fund R&D and pilot facilities to refine rearing conditions, temperature, humidity, and substrate formulations for high-performing species like BSF, while offering grants, soft loans, and tax credits to incentivize private investment in modular, climate-controlled insect farms (Joly and Nikiema, 2019; Shafer et al., 2022). At the same time, policymakers must establish harmonized food- and feed-safety protocols that address hygiene standards, contaminant limits, and potential allergenicity of insect products. Drawing on the EU's environmental-management regulations can provide a proven

TABLE 8 Summary of current policies and regulations in IBOWM.

Key aspect	Description	Examples
Regulatory frameworks	Formal guidelines that govern the production and commercialization of insect-derived products.	EU's Animal Feed Regulation (EU Regulation 2017/1017) (Rhoades et al., 2019).
Promotion of sustainable practices	Policies that emphasize environmentally sound and safe practices in insect farming operations.	Thailand's sustainable insect farming guidelines (Shahrani and Al–Surimi, 2018).
Harmonization of regulations	Challenges arising from the lack of consistent regulatory standards across regions, which hinder trade and market access.	Calls for a unified regulatory approach to support IBOWM development (Wang et al., 2019).
Public perception	Issues related to consumer misconceptions about the safety and nutritional value of insect-based products.	The necessity for public education initiatives to improve understanding and acceptance (Schmidt et al., 2018).

template to build consumer trust, streamline market entry, and ensure consistent quality control (Li M. et al., 2023; Papargyropoulou et al., 2014).

Equally essential is demonstrating IBOWM's economic and environmental viability. Mandating detailed life-cycle and cost–benefit analyses across various production scales and waste substrates will quantify returns on investment and guide policy decisions (Lisboa et al., 2024; Schilke et al., 2018). To lower entry barriers, financial support schemes, such as start-up grants, tax rebates, and public–private financing partnerships should be deployed, showcasing long-term savings from reduced waste disposal and revenue from high-value insect biomass. Finally, requiring comprehensive life-cycle assessments of energy use, greenhouse-gas emissions, and water footprints, alongside incentives for on-site renewable energy (solar, biogas), will minimize environmental impacts and align IBOWM with existing waste-management and agricultural policies to strengthen food security and local economies (Halloran et al., 2016b; Semernya et al., 2017; Smetana, 2023). Table 9 distills five key policy levers essential for driving a sustainable, scalable IBOWM sector.

5.3 Bridging knowledge gaps and setting future research priorities

IBOWM holds great promises for tackling waste management and bolstering food security, but several critical knowledge gaps must be addressed to unlock its full potential. First, harmonized regulatory frameworks are needed to enable the safe, scalable production of insects for food and feed, as regional inconsistencies currently limit market growth (Platonova et al., 2022). Second, detailed life-cycle assessments of different farming systems and organic substrates will be vital for quantifying environmental benefits and economic viability at scale (Schilke et al., 2018). Third, consumer acceptance remains a hurdle, research should probe public perceptions and develop targeted communication strategies that emphasize the nutritional and ecological upsides of insect-based products (Gilbert et al., 2018). Fourth, exploring synergies with agroecology and permaculture could yield innovative models for weaving insect farming into broader sustainable food systems (Wazzan et al., 2021). Fifth, long-term field studies are essential to track IBOWM's ecological and economic impacts over time and clarify its role in ecosystem resilience (Pope and Mazmanian, 2016). Sixth, to fully realize IBOWM's resource-recovery potential, rigorous monitoring of heavy-metal concentrations and antibiotic-resistance gene (ARG) profiles is essential, alongside substrate pretreatment or targeted remediation strategies; future research must refine these control measures and assess the long-term environmental impacts of persistent contaminants in insect-bioconversion systems (Liao et al., 2019; Zubair et al., 2023).

Beyond these priorities, optimization of species selection and waste-to-insect conversion ratios demand comparative trials across diverse substrates (Lisboa et al., 2024). To accelerate progress, policymakers should foster consortia linking universities, research centers, and industry, while dedicated training and knowledge-transfer programs can build capacity and disseminate best practices (Joly and Nikiema, 2019). Table 10 distills these gaps into actionable research directions, laying a roadmap for positioning IBOWM as a transformative, sustainable-development tool.

6 Conclusion

This study demonstrates the multifaceted advantages of IBOWM in strengthening ecosystem services and advancing sustainability. Through a detailed exploration of its environmental, economic, and social dimensions, we have shown that IBOWM effectively reduces organic waste, curbs greenhouse gas emissions, enhances soil health, supports biodiversity, and improves food security. Our structured framework reveals the

TABLE 9 Summary of policy enhancement recommendations for sustainable IBOWM.

Policy recommendation	Policy description	Implementation example /strategy
R&D and scale-Up incentives	Fund research and pilot facilities to optimize rearing parameters (temperature, humidity, substrates) for key species such as BSF.	Provide grants, soft loans and tax credits for modular, climate-controlled insect farms (Joly and Nikiema, 2019; Shafer et al., 2022).
Harmonized safety regulations	Establish unified food- and feed-safety protocols covering hygiene, contaminant limits and allergenicity.	Adopt EU-style environmental-management standards to streamline approvals and build consumer trust (Li M. et al., 2023; Papargyropoulou et al., 2014).
Economic viability analyses	Quantify returns on investment and environmental impacts across diverse production scales and waste substrates.	Mandate comprehensive life-cycle and cost–benefit analyses to guide policy and investment decisions (Lisboa et al., 2024; Schilke et al., 2018).
Financial support mechanisms	Lower entry barriers and stimulate private sector investment in IBOWM infrastructure.	Deploy start-up grants, tax rebates, and public–private financing partnerships that showcase long-term savings and revenue potential.
Environmental sustainability measures	Track energy use, GHG emissions and water footprints; encourage integration of renewable energy on-site.	Require holistic LCAs; provide incentives for on-site solar/biogas; align with existing waste-management and agricultural policies (Halloran et al., 2016b; Semernya et al., 2017; Smetana, 2023).

TABLE 10 Emerging research priorities and future directions for IBOWM.

Key area	Research gap	Future directions
Standardized regulations	Regional inconsistencies limit safe, scalable insect production for food and feed.	Develop harmonized guidelines for insect-rearing safety, quality control, and market access (Platonova et al., 2022).
Economic viability assessments	Limited data on the costs and benefits of scaling up insect farming systems.	Perform detailed life-cycle and cost–benefit analyses across diverse production models and waste substrates (Schilke et al., 2018).
Public education and awareness	Misconceptions hinder consumer acceptance of insects as feed/food.	Research consumer attitudes and craft targeted outreach that highlights nutritional and environmental advantages (Gilbert et al., 2018).
Integration with sustainable practices	Underexplored synergies between insect farming and agroecology/permaculture.	Investigate how IBOWM can complement ecological farming methods to build resilient, multifunctional systems (Wazzan et al., 2021).
Longitudinal impact studies	Scarcity of long-term data on IBOWM's ecological and economic outcomes.	Conduct extended field trials to monitor ecosystem health, productivity, and socio-economic impacts over time (Pope and Mazmanian, 2016).
Species–substrate optimization	Knowledge gap on the most efficient insect species and waste-to-biomass conversion ratios.	Run comparative trials of different insect taxa and organic substrates to identify high-yield, high-efficiency combinations (Lisboa et al., 2024).
Collaborative research and capacity building	Weak links among academia, industry, policymakers, and practitioners limit knowledge transfer.	Establish multi-stakeholder consortia and training programs to share best practices, build technical capacity, and align R&D with industry needs (Joly and Nikiema, 2019).
Contaminant monitoring and safety	Inadequate strategies and data on heavy metals and antibiotic-resistance genes (ARGs) within IBOWM systems.	Implement standardized monitoring protocols for heavy metals and ARGs, develop substrate pre-treatment and remediation strategies, and assess long-term impacts (Liao et al., 2019; Zubair et al., 2023).

complex interconnections among waste management, nutrient recycling, and economic opportunities, offering a comprehensive perspective on how IBOWM can bolster ecological health and sustainable development.

Moreover, our analysis of current policies and regulatory frameworks highlights critical gaps that impede the widespread adoption of IBOWM. Recognizing these challenges is essential for guiding future initiatives and ensuring that IBOWM can be seamlessly integrated into existing waste management systems. The regional case studies presented here provide practical lessons and best practices for overcoming these barriers, emphasizing the need for close collaboration between policymakers, researchers, and practitioners.

Finally, this study underscores the necessity for further research to address remaining concerns regarding the economic viability of IBOWM and its public acceptance. Future efforts should concentrate on establishing standardized regulations, undertaking comprehensive economic evaluations, and promoting educational initiatives to enhance public awareness. By fully harnessing the potential of IBOWM, we can make significant strides toward sustainable waste management, improved food security, and healthier ecosystems, ultimately paving the way for a more sustainable future.

Author contributions

LA: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. CM: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. WE: Visualization, Writing – original draft, Writing – review & editing. EC: Writing – original draft, Writing – review & editing. BE: Funding acquisition, Supervision, Writing – original draft, 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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