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Environmental Footprints Assessment: The Case For Insect Agriculture Over Traditional Livestock Systems

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Abstract

This review paper provides a comparative analysis of the environmental impacts associated with insect farming versus conventional livestock production. It examines key metrics including greenhouse gas (GHG) emissions, land use, water consumption, and feed conversion efficiency (FCE). Driven by a growing global population and increased demand for sustainable protein, insect farming is emerging as a viable alternative with significant entrepreneurial potential, and as a key component of circular economy models and alignment with broader sustainable development goals. Conventional livestock production is a significant contributor to environmental degradation, responsible for substantial GHG emissions, extensive land and water use, and often inefficient feed conversion. Conventional livestock production contributes significantly to global food system losses and inefficiencies. Only about 6% of the total global agricultural dry biomass produced is ultimately consumed as food by humans. In contrast, farmed insects generally exhibit significantly lower GHG emissions, require drastically less land and water, and demonstrate superior FCE, particularly when organic waste streams are utilized as feed. Life cycle assessments (LCAs) consistently highlight these benefits, though outcomes can vary based on insect species, rearing substrates, and system boundaries. While insect farming presents considerable environmental advantages, challenges such as energy requirements for climate control in rearing facilities, scalability (often linked to profitability), wide variations in margins depending on sales price and operational costs, market development, ethical considerations regarding insect welfare, particularly concerning sentience and slaughter methods, and the need for further research and regulatory development are also discussed. LCAs including waste treatment or by-product utilization, to accurately assess sustainability are crucial tools for a holistic sustainability evaluation of these emerging systems, though standardization of LCA methodologies for insects is still developing. The findings suggest that insect farming holds significant potential to contribute to a more sustainable global food system.

Keywords: ***insect farming, livestock production, environmental impact, sustainability, life cycle assessment (LCA), feed conversion efficiency (FCE), circular economy***

1. Introduction

The global population is projected to increase significantly in the coming decades, placing immense pressure on existing food systems to meet a rising demand for animal protein[1,2]. This rising demand, coupled with current production inefficiencies, poses a severe threat to global food security and environmental stability[3]. The EAT-Lancet report also emphasized the need for a shift towards more sustainable dietary patterns, partly due to the environmental impact of current animal production[4,5].

Conventional livestock production, currently the primary source of this protein, faces substantial and well-documented environmental challenges. It is a major contributor to climate change through significant greenhouse gas emissions, drives deforestation for pasture and feed cultivation, and leads to considerable water consumption and pollution[2,6,7]. The livestock sector is estimated to account for 14.5% to 18% of total anthropogenic GHG emissions in CO_2-equivalents[6,7]. Furthermore, it utilizes approximately 70% of all agricultural land and 30% of the planet's total ice-free land surface[1,7,8], and is responsible for over 8% of global human water use, primarily for the irrigation of feed crops[1,7]. The overall inefficiency of converting plant-based biomass to animal protein in traditional livestock systems contributes significantly to these environmental burdens, and the quantification study suggests that the livestock production results in losses of 81-94% of the initial feed energy and protein[9]. Consequently, the sustainability of current livestock practices is increasingly questioned, especially in light of forecasted climate changes and intensifying resource limitations[8,10]. The COVID-19 pandemic has further underscored the vulnerabilities in traditional protein supply chains and amplified the call for alternative, more resilient protein sources[10].

Insects have served as a traditional food source for billions of people across diverse cultures, particularly in Asia, Africa, and Latin America[1,10,11]. A comprehensive overview[3] of the global status of insects as a food and feed source has detailed their historical use and nutritional benefits. For example, palm weevil, crickets, grasshopper, and pallid emperor moth have been identified as insects with high demand as food in Nigeria, suggesting significant entrepreneurial potential[12]. The use of insects as feed, particularly species like the black soldier fly (*Hermetia illucens*), is also highlighted as a sustainable method to produce protein for pets, livestock, poultry, and aquaculture[13]. More recently, insect farming – encompassing both entomophagy (direct human consumption) and the use of insects in animal feed – has gained global attention as a potentially more sustainable alternative for protein production[7,8,11]. This interest has been significantly propelled by reports such as the FAO' - "Edible Insects: Future Prospects for Food and Feed Security"[5,14,15]. The sector is characterized by a growing number of 'entopreneurs', in Western contexts, driven by environmental and nutritional motivations[14].

Common species farmed include crickets (e.g., *Acheta domesticus*), mealworms (e.g., *Tenebrio molitor*), a species whose larvae can contain 46-54% protein and 25-36% fat on a dry matter basis[5], black soldier flies (BSF) (*Hermetia illucens*), and grasshoppers[1,11,16], along with buffalo worms, as the 'Big Four' food species commonly reared in Europe[14]. These insects can be reared for direct human consumption or processed into protein-rich ingredients for animal feed, benefiting poultry, pig, and aquaculture sectors [5–7,17,18]. There is a transition from wild collection to mini-livestock farming, highlighting the socio-economic and cultural factors involved in this shift[19]. Insects, alongside former foodstuffs, are promising alternative feed ingredients, owing to their high protein and fat content and their role in upgrading food waste streams[20].

A key advantage is the ability of many insect species to efficiently convert organic waste streams (such as food scraps and agricultural byproducts) into high-quality protein and fats [13,21–23], for instance, Chia et al.[24] reported that BSF larvae can reduce 30 metric tons of food waste to 10 metric tons of residue while producing 930 kg of dry biomass in a single day, enhancing their appeal from a circular economy perspective [6,16,17,24,25]. This emphasizes the potential of insect rearing within circularity, detailing both the opportunities and inherent challenges[26]. This aligns with the principles of a circular bio-economy, where waste is valorized [27].

This bioconversion potential positions insect farming as a key technology for valorizing bio-waste. It is estimated that 129 million tonnes of EU food waste suitable for insect meal production could be available by 2030, potentially generating a theoretical business value in billions[25]. The socio-economic benefits, such as poverty reduction and employment generation, especially in developing countries like Kenya, through BSFLM (black soldier fly larvae meal) replacing conventional poultry feed, have also been quantified [28].

Insect farming offers significant potential for synergies within the broader agri-food system. Its integration with other agricultural systems, for example, by using agricultural wastes or manure as feed for insects, can create closed-loop systems[16–18,24,26,29] frame this within a circular business model, where waste valorization is a central benefit. Numerous examples of food waste streams suitable for insect rearing, promoting circularity can be provided[23]. This contributes to a circular bio-economy, where waste products are valorized into valuable outputs like protein and bio-fertilizers (frass)[25]. Insect farming can contribute to achieving several Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger) through alternative protein, SDG 12 (Responsible Consumption and Production) via waste valorization, and SDG 13 (Climate Action) through reduced GHG emissions[18]. Thus insect farming is a key component of a circular economy, upgrading waste to valuable feed ingredients[20].

Given the significant environmental burden of conventional livestock and the proclaimed benefits of insect farming, a comprehensive comparison of their respective environmental footprints is crucial. Hence, the insect farming must be analyzed through a circular business model perspective to fully understand its economic and environmental viability[29]. Such an analysis can inform decision-making in policy development, guide industry practices, and influence consumer choices[7,11]. This review will systematically assess and compare the key environmental impacts of conventional livestock production with those of commercially relevant farmed insect species. The primary environmental aspects to be evaluated include greenhouse gas emissions, land use, water consumption, feed conversion efficiency, and the potential for waste valorization. Socio-economic implications and ethical considerations will also be touched upon, drawing from recent literature.

2 Environmental Impacts of Livestock Production

2.1Greenhouse Gas Emissions:

Conventional livestock production is a major global source of anthropogenic greenhouse gas (GHG) emissions, estimated at 14.5% to 18% of the total in CO_2-equivalents[6,7]. These emissions, alongside land and water use, make conventional animal agriculture a significant contributor to exceeding planetary boundaries[5]. A potent GHG, CH_4 is primarily produced through enteric fermentation in ruminant animals (especially cattle) and from manure management across various livestock types[7]. Another significant GHG, N_2O emissions arise mainly from manure management and the use of synthetic and organic fertilizers for feed crop production[6,7]. CO_2 emissions are linked to land-use change, particularly deforestation for pasture creation or feed crop cultivation (e.g., soy and corn), and from energy consumed throughout the production chain (housing, processing, transport)[7]. Beef and milk production from cattle are the largest contributors within the livestock sector, accounting for approximately 41% and 20% respectively of the sector's emissions. Pig meat and poultry contribute a smaller, yet still significant, share[1,7]. One FAO estimate[6], attributes about 9% of total anthropogenic CO_2, 37% of CH_4, and 65% of N_2O emissions globally to the livestock sector.

2.2Land Use:

The livestock sector is the world's largest user of agricultural land, utilizing approximately 70% of all agricultural land and 30% of the planet's total land surface[1,7,8]. This extensive land use is divided between grazing land for ruminants and cropland for the production of animal feed, such as soybeans and corn[1,11]. The expansion of pasture and feed crop cultivation is a primary driver of deforestation, particularly in tropical regions, leading to significant biodiversity loss and the release of stored carbon[6,7]. For instance, deforestation caused by pasture and feed crop expansion has been estimated to generate 8% of total anthropogenic CO_2 emissions[7,30]. The land footprint varies significantly between livestock types, with beef production generally requiring the most land per unit of protein, followed by pork and then poultry, reflecting differences in feed requirements and land use for grazing versus intensive feed production[7]. The vast land requirements for livestock are a major factor in their overall environmental footprint, contributing to habitat loss and competition for resources, with Alexander et al.[9] calculating that global harvested crops represent only a fraction of total cropland NPP due to residue losses.

2.3Water Consumption:

Livestock production exerts considerable pressure on global freshwater resources, accounting for over 8% of global human water use, with the majority (around 7%) attributed to the irrigation of feed crops[1,7]. Water is also essential for animal drinking, sanitation, and the processing of animal products[7]. The total water footprint (including blue, green, and grey water) varies significantly. For example, producing 1 kg of beef can require 15,000-22,000 liters of water or more, depending on the production system and feed source. In contrast, chicken and pork generally have lower water footprints[1,8]. Runoff from manure and fertilizer application for feed crops contributes to water pollution through eutrophication, contaminating surface and groundwater resources[7]. The high water demand for feed, particularly for water-intensive crops like soy and maize grown in water-scarce regions, is a major component of the overall water footprint of animal products[7].

2.4Feed Conversion Efficiency (FCE):

Feed conversion efficiency (FCE), often expressed as feed conversion ratio (FCR) (kg feed per kg product), is a critical factor in the environmental impact of livestock[7,8]. Conventional livestock generally exhibit relatively low FCEs. For instance, cattle may require 8-10 kg of feed to produce 1 kg of live weight, pigs around 3-5 kg, and poultry around 2-3 kg[1,6,8]. This inefficiency means that large quantities of crops, often human-edible like corn and soy, are diverted to animal feed. This creates competition for food resources and contributes significantly to the large land and water footprint of livestock[1,8]. This diversion of human-edible crops to animal feed is a key area where food system losses occur leading to substantial inefficiencies in converting crop calories and protein into animal products[9]. The production of these feed crops, in turn, has its own environmental impacts, including GHG emissions from fertilizer use and land-use change[7].

2.5Waste Generation and Management:

Livestock production generates vast quantities of manure. If not managed properly, manure can lead to significant environmental pollution, including the contamination of water bodies with excess nutrients (nitrogen and phosphorus) and pathogens, leading to eutrophication and health risks[7]. Manure management also contributes to air pollution through emissions of ammonia (NH_3), which can cause soil acidification and particulate matter formation, as well as GHGs like methane and nitrous oxide[7]. While manure can be a valuable organic fertilizer, the spatial disconnection between intensive livestock operations and croplands often hinders efficient nutrient recycling[7]. Inefficient manure management is also a source of nutrient loss from the food system[9]. Some agricultural systems aim to improve nutrient cycling through better integration of manure, for example, by using it as a component in bio-char production to enhance soil fertility, although this is context-dependent[31]. Furthermore, the processing of animal products generates additional waste and wastewater requiring treatment[32]. The sheer volume of waste and the challenges in its sustainable management are key environmental concerns.

2.6Impact on Biodiversity:

The expansion of livestock production is a leading driver of global biodiversity loss[6,7]. Habitat destruction and fragmentation occur primarily through the conversion of natural ecosystems, such as forests and grasslands, into pasture and land for feed crop cultivation[7]. This land-use change directly eliminates habitats for numerous plant and animal species. Pollution from livestock operations, including nutrient runoff, can degrade aquatic ecosystems and harm aquatic biodiversity[7]. Overgrazing can lead to land degradation and desertification, further reducing habitat quality[6]. The introduction of non-native livestock species can also disrupt local ecosystems. The overall pressure on land and water resources, coupled with pollution, makes conventional livestock farming a significant threat to terrestrial and aquatic biodiversity worldwide[7,11].

3 Environmental Impacts of Insect Farming

3.1 Greenhouse Gas Emissions:

Insect farming generally exhibits significantly lower GHG emissions per unit of protein compared to conventional livestock[5,6,11,18,21,33]. Most farmed insects, such as crickets (*Acheta domesticus*) and mealworms (*Tenebrio molitor*), produce negligible amounts of methane (CH_4) due to their different digestive physiology, which lacks the enteric fermentation common in ruminants[6,7]. It is found that species like *Tenebrio molitor*, *Acheta domesticus*, and *Locusta migratoria* did not emit CH_4 detectably[6,7,33]. While some feeder insects like *Pachnoda marginata* did emit CH_4, amounts were less than pigs or cattle per kg of weight gain. Nitrous oxide (N_2O) emissions are also considerably lower, primarily due to more efficient feed conversion and different manure (frass) composition and management[7]. For example, Halloran et al.[7] found insignificant CH_4 and N_2O levels from cricket farming systems in Thailand. The LCA study by Smetana et al.[22] provides a modular framework for assessing such emissions, emphasizing the importance of system boundaries and feed inputs. He found that insect-based feeds, particularly when utilizing waste streams like food processing by-products, can have significantly lower global warming potential (GWP) compared to conventional protein sources like fishmeal or soymeal, although manure-based diets could be less favorable without proper waste treatment consideration[34]. Similarly, a holistic sustainability assessment[35], quantified that the GHG emissions from BSF larvae valorizing organic waste showed significant reductions compared to the traditional waste management and conventional protein production. The primary GHG contribution from insect farming often stems from CO_2 produced by energy use for climate control (heating/cooling) in rearing facilities and, to a lesser extent, from feed production if dedicated crops are used[5,7]. However, the ability to use organic waste streams as feed can further reduce the carbon footprint associated with feed[23].

3.2 Land Use:

Insect farming requires substantially less land than conventional livestock production for an equivalent amount of protein[5,7,8,11,18,33]. This is attributable to several factors: insects can be reared at very high densities in vertically stacked systems (vertical farming), minimizing the direct land footprint of rearing facilities[6,7]. More importantly, many insect species, such as black soldier fly larvae (BSFL), can be efficiently reared on organic waste streams, including food waste and agricultural byproducts[16,17,23,24]. This drastically reduces or eliminates the need for dedicated land to grow feed crops, which constitutes the largest portion of the land footprint for livestock[7]. Oonincx and de Boer[36] estimated that 99% of the land use in mealworm production (using conventional feed) was for mixed grain feed[7]; if waste streams are utilized, this land use component becomes negligible. The LCAs[22,35] confirm these findings, showing that land use impacts are primarily driven by feed production and are dramatically lower when by-products or waste is the substrate[34]. This helps alleviate pressure on deforestation and frees up land for other uses, such as conservation or food crop production for direct human consumption[6].

3.3Water Consumption:

Insect farming typically consumes significantly less water compared to conventional livestock[1,5,7,8,33]. For example, the water footprint per gram of protein for mealworms is five times less than for beef[5]. Insects, being poikilothermic (cold-blooded), do not rely on evaporative cooling to maintain body temperature and obtain much of their water from their feed[7,8]. The species like *Tenebrio molitor* may not need additional drinking water if feed moisture is adequate[7,37]. Estimates show that producing 1 kg of insect protein requires a fraction of the water needed for 1 kg of beef or even poultry protein[1,8]. For example, crickets might require as little as 1 gallon of water per pound of produce, compared to vastly larger amounts for beef[1]. The LCA findings from Smetana et al.[22] and Rodríguez Escobar[35] support this, indicating substantially lower water footprints for insect systems, especially those utilizing waste streams which avoid irrigation demands for feed crops. This lower water demand is particularly advantageous in water-scarce regions. Furthermore, because insect farming can utilize waste streams as feed, the indirect water footprint associated with feed crop irrigation is also greatly reduced. The potential for water pollution from insect frass is also considered lower than from livestock manure due to its drier nature and different composition, though proper management is still necessary[7].

3.4Feed Conversion Efficiency (FCE):

Insects are renowned for their high feed conversion efficiency (FCE), meaning they require less feed to produce a unit of biomass or protein compared to conventional livestock[1,5,8,11,18,21,33]. For example, crickets require approximately 2.2 kg of feed per kg of edible weight, vastly more efficient than beef at around 25 kg of feed per kg edible weight[18]. Thus, crickets can have an FCR of around 1.7:1 (1.7 kg of feed for 1 kg of weight gain), whereas cattle might be 8:1 or higher[1,6,8]. The high FCE is potentially achievable using food wastes for insect mass production with various insect species on diverse waste substrates[12,23,38]. Some studies indicate insects can be twice as efficient as chickens, four times as pigs, and six to twelve times as cattle in converting feed to edible mass[1,8]. This superior efficiency is partly due to insects being poikilothermic, thus expending less energy on maintaining body temperature[1,8]. Additionally, a higher proportion of an insect's body is typically edible (up to 80%) compared to livestock (e.g., 40-55% for cattle/chicken) [1,6]. This high FCE reduces the overall demand for feed resources, thereby lessening the environmental impact associated with feed production, including land use, water consumption, and GHG emissions[7,11]. The ability of BSF larvae to convert organic by-products into insect biomass with high protein value is a key example[39].

3.5Waste Valorization (Frass):

A significant environmental benefit of insect farming, particularly with species like the black soldier fly larvae (BSFL), is their ability to valorize organic waste streams[6,13,16–18,20,24,33]. A detailed account of how various food wastes can be converted by different insect species, emphasizing the reduction in waste volume and the creation of valuable biomass is documented[23]. The LCA[35] demonstrates the practical application and environmental benefits of such a system for organic municipal waste. BSFL can efficiently convert various organic wastes, including food scraps, manure, and agricultural byproducts, into high-quality insect biomass (protein and fat) and a nutrient-rich residue called frass (insect excrement and exoskeletons)[17,40]. This bioconversion process helps to manage and reduce the volume of organic waste, which would otherwise end up in landfills, contributing to GHG emissions and potential pollution[17,25]. The frass produced is a valuable co-product, showing potential as an effective organic bio-fertilizer and soil amendment, capable of improving soil health and crop yields[16,18,40]. While direct studies on insect frass as bio-char are limited, research on bio-char from animal manure[31], demonstrates the potential of pyrolyzed organic waste from farming systems to increase soil organic carbon and improve nutrient availability in calcareous soils, suggesting analogous benefits could be explored for frass. This aspect is crucial to the circular economy models[26,29]. This creates a circular economy model, where waste is transformed into valuable resources, reducing the need for synthetic fertilizers and contributing to more sustainable agricultural practices[6,16,21]. A study[40] specifically investigated BSFL residues from food scrap processing and found mixed effects on corn plant growth, indicating potential for soil amendment but also a need for post-processing of the frass. The recycling of bio-waste by insects can also contribute to significant socio-economic benefits like employment and poverty reduction in specific contexts[28].

3.6Potential Impact on Biodiversity:

The potential impacts of insect farming on biodiversity are multifaceted and generally considered more positive compared to conventional livestock, particularly if it leads to a reduction in livestock production[6,7]. By requiring significantly less land, especially if waste streams are used as feed, insect farming can reduce pressure on natural ecosystems, thereby mitigating habitat destruction and fragmentation – key drivers of biodiversity loss[6,7]. If insect meal replaces fishmeal in aquaculture feeds, it can alleviate pressure on wild fish stocks, contributing to marine biodiversity conservation[7,18].

However, considerations include the potential ecological risks from the escape of non-native farmed insect species into new environments, although this is generally considered manageable in contained systems[7,10]. The challenges and importance of sustainable sourcing and farming practices to avoid negative biodiversity impacts have been studied[19]. There is a possibility of over-collection from the wild if farming is not established effectively. Additionally, the concentration on a few farmed insect species might draw attention away from conserving the biodiversity of wild edible insects[7]. Furthermore, the ethical dimension of insect farming, including questions of sentience and appropriate rearing and slaughter methods, is an emerging area of research with implications for public perception and sustainability claims. For instance, the UK insect farmers are found grappling with these ethical ambiguities, often developing individualized care practices in the absence of formal welfare codes[38]. There is a need for more research and policy development regarding welfare in insect farming[41]. Overall, by offering a more resource-efficient protein source, insect farming has the potential to lessen the biodiversity footprint associated with global food production.

4 Comparative Environmental Footprints

When directly compared, insect farming generally outperforms conventional livestock production across key environmental metrics. Table 1 summarizes the comparative environmental footprints of livestock versus insect species.

Insects like crickets and mealworms produce negligible CH_4 and N_2O. The primary GHG from insect farming is CO_2 from energy use, which can be significant if facilities rely on fossil fuels for climate control. Livestock, particularly ruminants, are major emitters of CH_4, N_2O, and CO_2 (from land-use change and energy). LCA shows that insect-based food and feed can have lower GWP than conventional animal products, especially when utilizing waste or by-products as feed[22]. Insects require dramatically less land. Vertical farming systems minimize direct land use, and the ability to use waste as feed nearly eliminates the vast land requirements for feed crop production, which is the dominant land use factor for livestock.

For example, Oonincx and de Boer[36] found 99% of land use for conventionally-fed mealworms was for feed; this becomes negligible with waste-based feed[7]. Insects consume far less water. Their poikilothermic nature and ability to derive water from feed reduces direct water intake. Crickets, for instance, may need only 1 gallon of water per pound of produce, a fraction of beef's requirement of 15,000-22,000 liters per kg[1]. Using waste feed also reduces the indirect water footprint from feed crop irrigation. Insects are significantly more efficient in FCE. Crickets can achieve an FCR of ~1.7:1, while cattle can be 8:1 or higher[1,6,8]. This means less feed is needed per unit of protein, reducing overall resource demand. Smetana et al.[22] provide a meta-analysis of LCA studies, confirming these general trends and highlighting the variability based on specific system parameters.

Other studies have also corroborate the superior FCE of many insect species, noting protein content can range from 23% to 76% (dry matter) depending on species and life stage, comparing favorably to conventional feedstuffs[5,33].

5 Factors Influencing Environmental Impact:

The environmental impact of both systems is variable and depends on several factors. The type of animal (e.g., beef generally has a higher impact than poultry), the farming system (intensive vs. extensive), feed composition (locally sourced vs. imported, type of crops), and manure management practices significantly influence the footprint.

The specific insect species, the rearing substrate (use of waste streams versus dedicated feed makes a substantial difference[23,35], farming system design (e.g., vertical vs. horizontal, level of automation), and energy sources used (especially for climate control) are key determinants of environmental impact. Feed, farming processes, and energy are major hotspots in insect LCAs and the choice of diet for insects is critical, with low-value food processing by-products and specific waste streams offering the best environmental performance, while protein-rich diets or manure can increase impacts if not managed properly[22]. The choice of feed, for instance, drastically alters the land use and GHG emissions associated with insect production; Halloran et al.[42] noted that when mealworms are fed grains, their GWP can be comparable to pork or chicken, but this drops significantly if waste streams are used.

6 Life Cycle Assessment (LCA) Studies:

Several LCA studies have compared insect farming with livestock production. For example, cricket farming in Thailand had a lower GWP than broiler chicken farming[7,42]; mealworms fed conventional grain had a GWP comparable to or higher than pork and chicken but used significantly less land[7,10,36]. Smetana et al.[22] reviewed several LCA studies on insect production, establishing a modular framework to improve comparability and identify data gaps. Their work emphasizes that while insects fed conventional feed can have impacts comparable to efficient livestock like poultry, the use of food waste or by-products as feed drastically improves the environmental profile. A detailed holistic sustainability assessment (including LCA) of an improved organic waste collection system valorized through BSF showed significant environmental benefits in terms of reduced global warming potential and eutrophication compared to conventional composting and incineration when system expansion (avoided products) was considered[35].

This study highlighted the sensitivity of results to energy sources for BSF rearing and processing, and the critical role of avoided burdens from utilizing waste. However, the GWP for insects is highly sensitive to the feed source; using waste streams dramatically lowers impacts. Methodologies, system boundaries (e.g., inclusion of land-use change, end-of-life of waste), and assumptions (e.g., energy mix for electricity) vary between LCAs, making direct comparisons sometimes complex. Another review[42] of LCA studies highlighted that only a few insect species had been assessed, with most studies focusing on GWP and energy use, and called for more empirical data from diverse, scaled-up systems.

Many LCAs highlight the significant contribution of feed production to the overall environmental footprint of both insects (if conventionally fed) and livestock. The LCAs[34] on Black Soldier Fly larvae production for feed, comparing various diets (e.g., protein-rich, manure, food by-products) found that environmental performance heavily depended on the diet, with food processing by-products being most sustainable, while production of insect-based meat substitutes using these by-products was 2-5 times more environmentally beneficial than traditional meat products.

7 Challenges and Limitations of Insect Farming:

Despite its potential, insect farming faces several challenges. Transitioning from small-scale or pilot operations to large-scale industrial production requires significant technological and logistical development[26]. The economics of insect farming are crucial for scalability as the profitability of insect farming (e.g., for *H. illucens*, *T. molitor, A. domesticus*) is highly variable, influenced by factors such as sales prices variations depending on species, processing, and market (feed vs. food) [43]. The information gap is hindering entrepreneurial uptake[12]. There are difficulties in turning wild collectors into consistent mini-livestock farmers, citing issues like access to capital, training, and stable markets[19]. Many insect farming ventures in Europe and North America are start-ups, often with limited entomological knowledge among founders, facing challenges in scaling up from feeder insect operations or novel food businesses[14].

Table 1: Comparative environmental footprints of livestock vs. insect species

Protein Source	**Crude Protein (% DM)**	**Crude Fat (% DM)**	**GHG Emissions (kg CO_2-eq per kg product type)**	**Land Use (m^2 per kg product type)**	**Water Consumption (L or m^3 per kg product type)**	**Feed Conversion Ratio (FCR) (kg feed per kg gain type)**
LIVESTOCK						
Beef	~20-22 (typical cooked)	~10-20 (typical cooked)	~23.8 - 45.4 edible mass[7] 14.8 kg[1]	High(qualitative); 30% world surface land area[7]; 10x mealworm protein[11]	High; ~3x mealworms[7]; 22,000-43,000 L/kg[1]; 16.8 L/g protein[1]	~25 kg feed/kg edible weight[18]; 10%[1]
Pork	~25-30 (typical cooked)	~15-25 (typical cooked)	~4.41 edible mass[7]; 3.8 kg[1]	Moderate; 2-3.5x mealworm protein land use[11]	3,500 L/kg[1]; 5.8 L/g protein[1]	5.9[1]
Poultry (Broiler Chicken)	~30-35 (typical cooked)	~5-15 (typical cooked)	~2.9 - 4.06 edible mass[7]; 1.1 kg[1]; 32-167% higher than mealworms /g protein[33]	Moderate; 2-3.5x mealworm protein land use[35]	Comparable to mealworms[7]; 2,300 L/kg[1]; 5.2 L/g protein[1]	1.7-2.3[1]
INSECTS						
Mealworms (*Tenebrio molitor*)	46-54[5]	25-36[5]	~2.29 - 2.7 per kg edible mass[7]; GHG lower than pork, chicken, beef /kg protein[7]	99% for mixed grain feed[36]; 1.5-1.52[7]; 3.6[36]	Water footprint comparable to chicken[7]; 0.003[42]; 1.6[1]	2.2 fresh weight on mixed grains[42]; 2.2 kg[22]; 3.8-5.3[42]
Crickets (*Acheta domesticus, Gryllus bimaculatus* etc.)	59-72[5]	10-23[5]	2.57 per kg edible mass (fresh)[44]; 4.35 per kg protein[44]	0.0000116 edible mass (fresh)[44]	0.42 per kg edible mass (fresh)[44]	2.50 live weight crickets[44]
Black Soldier Fly Larvae (*Hermetia illucens*)	34-42[5]	25-58[5]	1.36-15.1 DM meal, conventional feed[22]; 6.42 to 5.3 DM larvae, waste/by-product feeds[22]	0.0032-7.03 DM meal conventional feed[34]; 16.8 to 1.9 DM larvae waste/by-product feeds[22]	0.8-1.1 DM larvae food processing by-product[22]	Highly variable by diet: e.g., 2.8-3.3 kg DM larvae (on okara/distiller's grains[22] 22-109 DM meal on grains[34]
Housefly Larvae (*Musca domestica*)	51-60[5]	25-28[5]	0.77 DM meal[22]; 61% lower GWP than fishmeal/soybean meal mix[33]	0.032 DM meal[22]; 98% lower land use than fishmeal/ soybean meal mix[33]	10,309 DM larvae meal[33]	4 fresh larvae[22]

Increased feeding costs due to high insect meal prices and less favorable FCR suggests current economic non-viability in certain cases[45]. There is a need for technological advancements for sustainable protein recovery from novel sources like insects[27].

Climate control for insect rearing facilities can be energy-intensive, potentially offsetting some GHG benefits if reliant on fossil fuels[7] which is a sensitive parameter in BSF systems[11]. Efficient energy use is a key challenge for sustainable insect farming, as maintaining optimal temperatures for insect growth (e.g., 27-35°C for many species) can be costly[5]. Regulations for using insects as food and feed, and for using certain waste streams as insect feed, are still evolving as a key factor in many regions[29]. 'Institutional vertebratism' where existing food and welfare regulations (e.g., EU Novel Food Regulation) are ill-suited for invertebrates, create regulatory blind spots and delay development[14]. A review[46] of the legal framework for insects as feed, highlights differences across countries and the ongoing evolution of these regulations. Cultural barriers and neophobia towards entomophagy exist in many Western societies, though this is gradually changing which emphasizes the importance of addressing socio-cultural perceptions[19,21,46]. While entomophagy is traditional in many cultures, farming insects for human consumption is novel even in those contexts, and Western acceptance is a key hurdle[14].

Further research is needed on optimizing rearing systems for a wider variety of insect species, standardizing production methods, and fully understanding long-term environmental and ecological impacts and more standardized LCA approaches.[22]. There is a need for more research on insect physiology (e.g., growth regulation, nutrient requirements) and disease control for mass rearing systems[5]. More attention and research is needed to insect sentience and welfare in farming practices[38,41].

8 Future Perspectives and Research Needs

Future progress will rely on technological innovation, including automation in insect rearing and processing to reduce labor costs and improve efficiency. The potential role of fermentation in pre-treating food wastes for insect farming can be explored, which could enhance nutrient availability and safety[23]. Genetic improvements in farmed insect species could enhance productivity, nutritional value, and disease resistance. Further optimization of feed formulations, particularly from diverse organic waste streams, is crucial for sustainability and cost-effectiveness. The development of safe and affordable insect farming at scale, including optimizing housing, feeding, and processing methods, is a key challenge[5]. The need for innovation in biomass choice, processing technologies like mild separation, and understanding protein functionality for developing new protein sources, including insects needs to be emphasized[27]. There is a pressing need for clear, science-based guidelines and standards for insect farming, processing, and product safety[19,29]. Policy incentives that support sustainable protein production, including insect farming, could accelerate the sector's growth and its positive environmental contributions. There is a need for regulatory frameworks that specifically address invertebrates[14]. Harmonization of regulations across different countries will also be important for international trade[46]. Strategies to overcome cultural barriers and promote insects as a safe, nutritious, and sustainable food and feed source are essential[19]. This may include public education campaigns, transparent labeling, and development of attractive and palatable insect-based food products. It is suggested that consumer acceptance of insects as feed might be higher than for direct food use, but this requires further investigation and clear communication about benefits[46].

Key areas for future research include: Comprehensive LCAs for a wider range of insect species and diverse production systems, including long-term environmental impacts of large-scale operations[22,34,42]; detailed risk assessments concerning allergens, potential pathogens associated with insect farming or feed substrates[24], and the ecological impact of potential escapes of non-native farmed species[5], human health aspects, including allergies and microbial risks associated with edible insects[21]; socio-economic impact[28] studies to understand the effects of a broader shift towards insect-based protein on livelihoods, food security, and local economies, particularly in developing countries[12,19]; research on effective business models for insect farming[29,43]. Further investigation into insect welfare, sentience, and the development of humane rearing and slaughter practices is needed, as current practices are largely unregulated and ethical concerns may impact consumer acceptance and the industry's sustainability image[38,41].

9 Conclusion

The comparison between insect farming and conventional livestock production reveals significant environmental advantages for insects, particularly concerning greenhouse gas emissions, land use, water consumption, and feed conversion efficiency. Livestock production, while a vital source of protein, carries a substantial environmental footprint that is increasingly unsustainable, exacerbated by inefficiencies such as the 44% of harvested crop dry matter being lost or diverted before human consumption. Insect farming, especially when integrated into a circular economy model that valorizes organic waste streams offers a compelling pathway to reduce these impacts. Insects convert feed into protein far more efficiently than conventional livestock, and their production can alleviate pressure on land and water resources. These environmental benefits are strongly supported particularly when low-value by-products or waste streams are used as feed.

However, the realization of insect farming's full potential requires addressing existing challenges, including the energy demands of climate-controlled rearing, scaling up, navigating evolving regulatory landscapes and fostering broader consumer acceptance including ethical production that considers insect welfare. Continued research, technological innovation supportive policy frameworks, and consumer education are crucial. Detailed and standardized LCAs are essential to guide sustainable development and identify true environmental hotspots and benefits as the existing studies often rely on limited empirical data and inconsistent system boundaries, making direct comparisons difficult. The economic viability also needs careful consideration.

Insect farming, a highly promising and complementary approach within a diversified and more sustainable global food system, has its capacity to transform low-value organic wastes into high-value protein and other co-products (such as frass, which can be used as fertilizer, and bio-char which can improve soil in semi-arid regions) positions it as a key contributor to future food security and environmental stewardship. The entrepreneurial drive seen in various regions indicates a growing recognition of its economic and ecological value. Insect farming can deliver tangible socio-economic benefits, contributing to poverty alleviation and job creation.

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