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Review

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Beneficial Uses of Insects

Circular economy of insect farming as an innovative strategy for weed management

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Weeds can reduce crop yields by 19% to 100%, yet their management remains heavily dependent on synthetic herbicides, despite growing concerns about environmental pollution, biodiversity loss and risks to human health. Here, we provide a critical review on the ecological management of weeds through edible insect farming technologies. We analyse existing literature on the effects of weeds on crop production, the current weed management practices and factors influencing their efficacies. Furthermore, we present current studies on the potential for using insects as a nature-based approach for weed management, focusing on the nutritional quality of different weed species and properties that make weeds a suitable diet for edible insect production. Studies show that insects have the unique ability to consume multiple weed species, converting them into nutrient-rich biomass containing 35% to 61% crude protein, which is highly valuable for human diets and livestock feed. Insects fed on diets derived from weeds have a 34% to 100% growth rate, reproduction, survival and weight gain. Furthermore, the frass amendment derived from insect-based bioconversion of different weed species has been shown to improve soil health and crop yields, while also effectively suppressing pests, pathogens, and weeds. We provide recommendations on strategies for harnessing the full potential of weeds as diets for mass production of edible insects. This information is key in guiding researchers and policymakers in public and private sectors to advance insect-based technologies as an innovative and transformative approach for weed management, sustainable agriculture, food security and improved livelihoods through circular economy.

Keywords: weed control, edible insect, frass amendment, regenerative agriculture, food security

Introduction

The global human population is projected to increase by 60 million per annum, reaching 9.7 billion people by the year 2050 (United Nations 2022). This surge in population will ultimately intensify the demand for food production, especially in the Global South, putting more pressure on the already constrained arable lands (de Graaff et al. 2011, Van Ittersum et al. 2016). The productivity of agricultural lands is slowly declining due to intensive pressure from biotic and abiotic stress, exacerbated by climate change (Mabhaudhi et al. 2016, Hadebe et al. 2017, Tuninetti and Davis 2026). Biotic pressure from herbivorous pests, weeds, and pathogens collectively affects all components of food security, from overall production to physical availability, economic access, nutritive value and safety (Savary et al. 2019). However, practices that seek to reduce their impact often cause adverse environmental impacts, rendering agriculture unsustainable.

Weeds are, in most cases, the leading biotic constraint in crop production, but accurate quantification of their economic impact is frequently hampered by their diversity and heterogeneous climatic and edaphic factors (Milberg and Hallgren 2004, Adeux et al. 2019). The ecological-niche-based theories postulate that the economic loss due to weed infestation is intense when they occupy the same niche as the crop (Smith et al. 2010, Adeux et al. 2019). Within this scope, high functional diversity is expected to induce resource use complementarity, ultimately reducing niche overlap probability, yet it has been reported to cause competitive hierarchies (Smith et al. 2010, Navas 2012, Funk and Wolf 2016, Adeux et al. 2019). Modern cropping systems range from simple monoculture to

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highly sophisticated mixed farming, which corresponds to differences in weed management practices (Smith et al. 2010). Such pragmatic diversities and other methodical challenges limit the quantification of yield loss on temporal and spatial scales, as well as effective management practices.

Weeds account for the highest crop yield loss, yet their management relies heavily on synthetic herbicides. Yield loss is estimated to vary between 19% and 100% based upon numerous factors such as field management practices, species of the weed and host crop, nutrient availability, and precipitation (Milberg and Hallgren 2004, Olorunmaiye and Olorunmaiye 2009, Mushagalusa et al. 2016, Soltani et al. 2016). For instance, parasitic weeds such as *Striga* spp. (Lamiales: Orobanchaceae) can cause up to 100% yield loss (Emechebe et al. 2004, Begna 2021), whereas invasive weeds such as *Parthenium* spp. (Asterales: Asteraceae) not only cause crop yield reduction but also produce parthenin, a genotoxic compound that causes hay fever, dermatitis and asthma, and contaminates meat and dairy products (Strathie et al. 2021). *Parthenium* weed also acts as a source of nectar for *Anopheles* spp. (Diptera: Culicidae), supplying carbohydrates that sustain adult survival (Nyasembe et al. 2015). Over 97% of farmers in developed nations rely on tillage and herbicide application for weed control, whereas in developing nations, smallholder farmers predominantly depend on manual weeding (Gianessi 2013, Corbeels et al. 2020). Although mechanical weeding is often more labor-intensive, it is environmentally friendly, enhances nutrient cycling, and increases habitat complexity, thereby supporting the diversity and abundance of nontarget microorganisms and arthropods (Helander et al. 2018, Iddris et al. 2023). Herbicides directly reduce soil functions and can drift in surface and sub-surface water flow, consequently impacting aquatic ecosystems (Van Stempvoort et al. 2014, Stevanovic and Gasic 2019).

Overreliance on herbicides imposes strong selection pressure on weed populations, accelerating the evolution of herbicide resistance. For instance, resistance to acetyl-CoA carboxylase (ACCase) inhibitors, acetolactate synthase (ALS) inhibitors, glyphosate, paraquat, and glufosinate herbicides has been widely reported in numerous weed species in Poaceae family such as *Beckmannia*, *Eleusine*, *Avena*, *Echinochloa*, *Poa*, *Hordeum*, *Lolium*, *Sorghum*, *Setaria*, *Urochloa*, *Digitaria*, *Bromus*, and *Alopecurus* spp., as well as broadleaf weeds in the Amaranthaceae (*Kochia* and *Amaranthus* spp.), and Asteraceae families (*Chromolaena*, *Ambrosia*, *Conyza*, and *Bidens* spp.) (Ashworth et al. 2014, Iwakami et al. 2015, Keshtkar et al. 2015, Owen et al. 2015, Varanasi et al. 2015, Fernandez-Moreno et al. 2017, Peterson et al. 2018, Gaines et al. 2020, Sutherland et al. 2025). Consequently, agricultural ecosystems are often dominated by a few weed species that are tolerant to the existing control methods, yet they are poorly equipped to confer critical agroecosystem functions. While adversely affecting biodiversity, the selectivity of the herbicides applied often creates opportunities for invasive weeds, resulting in a cyclic arms race that renders agroecosystems vulnerable. Previous research has elucidated the inherent risks of excessive herbicides, calling for alternative sustainable approaches (Harker and O'Donovan 2013, Egan et al. 2014, Van Stempvoort et al. 2014, Peterson et al. 2018, Stevanovic and Gasic 2019, Gaines et al. 2020, MacLaren et al. 2020).

Here, we offer an innovative approach to weed management through the mass production of edible insects. Edible insect farming has recently emerged as a multifaceted strategy for valorizing low-value agricultural wastes into high-quality products such as protein-rich food, livestock feed and organic manure while also creating resilient livelihoods as a source of income. The mass rearing of insects as mini-livestock is still an emerging sector with limited studies about its agricultural potential. While previous research has documented the potential of edible insects in waste valorization (Kelemu et al. 2015, Dobermann et al. 2017, Tanga et al. 2021, Beesigamukama et al. 2023, Megido et al. 2024), there is limited information about the potential of these mini-livestock in sustainable management of weeds. We synthesize the literature to explore the unrealized potential of edible insects as a sustainable approach to the ecological management of weeds in agricultural systems. The critical appraisal of previous research identifies 5 synergistic benefits of integrated circular weed management using edible insect farming technologies: (i) reduced reliance on herbicides and associated adverse effects; (ii) alleviation of weed-induced biotic stress, leading to enhanced crop productivity; (iii) valorization of weed biomass into quality insect protein; (iv) generation of insect frass which can be used as soil amendment; and (v) diversification of farm income streams through the co-production of crops, feed, and frass soil amendment. The vision of this approach is to harness the competitive and ruderal traits of weeds and develop resilient agroecosystems and sustainable livelihoods.

Economic Impact of Arable Weeds

Weeds compete with food crops for resources, resulting in a significant reduction in crop yield. They often possess numerous traits, such as rapid growth, dense canopy, extensive lateral spread, and shoot morphology, that make them stress-tolerant, competitive, and ruderal compared to cultivated crops (Fig. 1). However, crop yield loss due to weed infestation may vary based on numerous factors such as, crop species, weed communities, cultural practices, edaphic factors, and environmental conditions (Table 1) (Milberg and Hallgren 2004, Gibson et al. 2017, Ramesh et al. 2017). Apart from competition, weeds may also release allelopathic exudates that negatively affect crop physiology. Over 200 weed species with diverse life forms and growth habits have been documented to possess allelopathic effects on a broad range of crop species (Qasem and Foy 2001, Falquet et al. 2014, Jabran et al. 2015, Reiss et al. 2018). Weeds such as *Striga* spp. and *Orabanche* spp. (Lamiales: Orobanchaceae), and *Cuscuta* spp. (Solanales: Convolvulaceae) may also deprive crops of nutrients through parasitic interactions, resulting in substantial yield losses (Håkansson 2003, Parker 2013, Aly and Dubey 2014, Kaiser et al. 2015, Těšitel 2016, Hegenauer et al. 2017, Kebede and Ayana 2018, Albanova et al. 2023, Moncalvillo and Matthies 2023). These adverse impacts often lead farmers to perceive weeds as a major agricultural challenge, often resorting to synthetic pesticides as their first line of defense.

Unlike mechanical weed control, the nonselectivity of herbicides often induces substantial shifts in the relative abundance and diversity of weed communities, resulting in the proliferation of adaptive weed species. Such ecosystem selection tends to eliminate various susceptible weed species while allowing resistant biotypes to reproduce and flourish (Harker and O'Donovan 2013, Seyed 2014). Herbicides constitute the highest proportion of pesticide use and the leading cause of biodiversity loss. By 2021, South and North America, with a total population estimate of 900 million people, recorded the highest rate of herbicide application, averaging 1 million metric tonnes,

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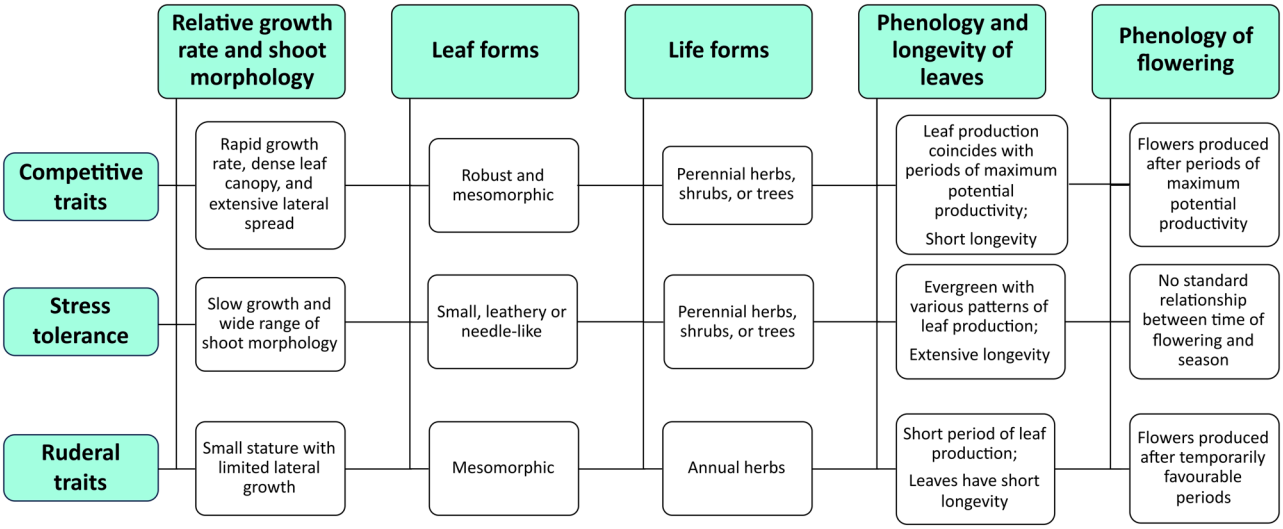


Fig. 1. Traits that make weeds competitive, stress-tolerant, and ruderal in agroecosystems.

Table 1. Identity of common weeds and their economic implications on crop production

Crop	Weed species	Weed family	Mechanisms	Average yield loss (%)	Potential loss (US billion $)	Reference(s)
Maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.) and millets (*Eleusine coracana* (L.) Gaertn.)	Purple witchweed (*Striga hermonthica* Del. Benth)	Orobanchaceae	Competition and parasitism	20 to 80	-	(Khan et al. 2006, Ejeta 2007, Kanampiu et al. 2018, Begna 2021)
Maize (*Z. mays*)	Combined weed effect	-	Competition and allelopathy	10 to 73.7	0.012 to 26.7	(Soltani et al. 2016)
Maize (*Z. mays*)	Parthenium weed (*Parthenium hysterophorus* L.)	Asteraceae	Competition and allelopathy	21 to 54	-	(Safdar et al. 2015)
Cassava (*Manihot esculenta* Crantz.)	Combined weed effect	Malvaceae, Ateraceae, Poaceae, Fabaceae and Convolvulaceae	Competition, allelopathy and parasitism	46 to 95	-	(Olorunmaiye and Olorunmaiye 2009, Mushagalusa et al. 2016)
Rice (Oryza sativa L.)	Alkali bulrush (*Bolboschoenus maritimus* L.), Jungle rice (*Echinochloa colona* L.), Rice sedge (*Cyperus difformis* L.) and Wild rice (*Oryza longistaminata*)	Poaceae	Competition	47 to 49	-	(Johnson et al. 2004)
Rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.)	Grass species, field pansy (*Viola arvensis* Murray) and Common fumitory (*Fumaria officinalis* L.)	Poaceae, Violaceae and Papaveraceae	Competition and allelopathy		5.4	(Milberg and Hallgren 2004)
Wheat (*T. aestivum*) and barley (*H. vulgare*)	Cleavers (*Galium aparine* L.), Common poppy (*Papaver rhoeas* L.), Mayweed (*Matricaria* spp.), and Wild radish (*Raphanus raphanistrum* L.)	Rubiaceae, Papaveraceae, Asteraceae, and Brassicaceae	Competition and allelopathy	11.3	-	(Wilson and Cussans 1983)
Wheat (*T. aestivum*), oats (*A. sativa*), barley (*H. vulgare*), canola (*Brassica napus* L.), pulses, and lupins (*Lupinus* spp.)	Combined weed effect	Asteraceae, Basellaceae, Poaceae, Convolvulaceae, Fabaceae, etc.	Competition, allelopathy and parasitism	17	0.86	(Jones et al. 2005)

(Continued)

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Table 1. (Continued)

Crop	Weed species	Weed family	Mechanisms	Average yield loss (%)	Potential loss (US billion $)	Reference(s)
Wheat (*T. aestivum*)	Cheat grass (*Bromus tectorum* L.), Jointed goatgrass (*Aegilops cylindrica* L.) and Annual ryegrass (*Lolium perenne* L. ssp. *Multiflorum*)	Poaceae	Competition	10 to 92	-	(Rydrych and Muzik 1968, Appleby et al. 1976, Ogg and Seefeldt 1999)
Wheat (*Triticum aestivum* L.)	Combined weed effect	Asteraceae, Poaceae, and Brassicaceae	Competition and allelopathy	25.4 to 33.2	1.13 to 2.19	(Flessner et al. 2021)
Wheat (*T. aestivum*)	Italian ryegrass (*Lolium multiflorum* Lam.)	Poaceae	Competition and allelopathy	20 to 30	-	(Scursoni et al. 2012)
Rice (Oryza sativa L.)	Combined weed effect	Asteraceae, Poaceae, and Brassicaceae	Competition and allelopathy	15 to 66	4.42	(Gharde et al. 2018)
Soybean (*Glycine max* (L.) Merr.)	Common sunflower (*Helianthus annuus* L), Common cocklebur (*Xanthium strumarium* L.), and Chinese jute (*Abutilon theophrasti* Medik.)	Asteraceae and Malvaceae	Competition and allelopathy	12 to 76	-	(Mortensen and Coble 1989, Mosier and Oliver 1995, Hock et al. 2006, Datta et al. 2017)
Soy bean (*G. max*)	Combined weed effect	Asteraceae, Basellaceae, Poaceae, Convolvulaceae, Fabaceae, etc.	Competition, allelopathy and parasitism	11.9 to 28.7	-	(Vollmann et al. 2010)
Soybean (*G. max*)	Barnyard grass (*Echinochloa crusgalli* L.), Asiatic dayflower (*Commelina communis* L.), and Gulf Leafflower (*Phyllanthus fraternus* Webster)	Poaceae, Commelinaceae and Euphorbiaceae	Competition and allelopathy	20 to 77	1.56	(Kurchania et al. 2001, Gharde et al. 2018)
Peanut (*Arachis hypogeae* L.)	Alexander grass (*Brachiaria plantaginea* Hitchc.), Crabgrass (*Digitaria horizontalis* Willd.), and Black jack (*Bidens pilosa* L.)	Poaceae and Asteraceae	Competition and allelopathy	70 to 92	-	(Agostinho et al. 2006)
Niger (*Guizotia abyssinica* L.), greengram (*Phaseolus radiatus* L), sesame (*Sesamum indicum*), and pigeonpea (*Cajanus cajan* L.)	Field dodder (*Cuscuta campestris* Yuncker)	Convolvulaceae	Competition and parasitism	17.8 to 85.9	-	(Farah 2004, Mishra et al. 2007)
Potato (*Solanum tuberosum* L.)	Barnyard grass (*Echinochloa crus-galli* L. Beauv.), Green foxtail (*Setaria viridis* L.), Quackgrass (*Elytriga repens* L.), Common lambsquarters (*Chenopodium album* L.), Kochia (*Bassia scoparia* L.), Pigweed (*Amaranthus retroflexus* L.), and Hairy nightshade (*Solanum physalifolium* Rusby)	Poaceae, Amaranthaceae, and Sollanaceae	Competition and parasitism	12 to 61	0.06 to 0.47	(Tonks et al. 2000, Hutchinson et al. 2003, Hutchinson 2014, Ganie et al. 2023)

whereas Africa, with a total population estimate of 1.2 billion people, recorded the lowest application rate of 65,000 metric tonnes (Fig. 2) (FAOSTAT 2021, Ritchie et al. 2022). Excessive application herbicides recorded in various American and Asian countries represents a critical threat to agroecosystem resilience (Fig. 2). Notably, recent studies in China have reported high levels of atrazine in aquatic ecosystems exceeding the national threshold rate of 1.0 mg kg^{-1} (Liu et al. 2020a), whereas in Costa Rica, up to 22.8 and 4.8 µg L^{-1} rates of diuron and terbutryn, respectively, have been recorded (Carazo-Rojas et al. 2018). Furthermore, previous research from Mexico revealed the highest levels of glyphosate residues in aquatic ecosystems ranging from <0.13 to 36.71 µg L^{-1} (Rendón-Von Osten and Dzul-Caamal 2017), whereas a range of 0.05 to 1.2 mg kg^{-1} of

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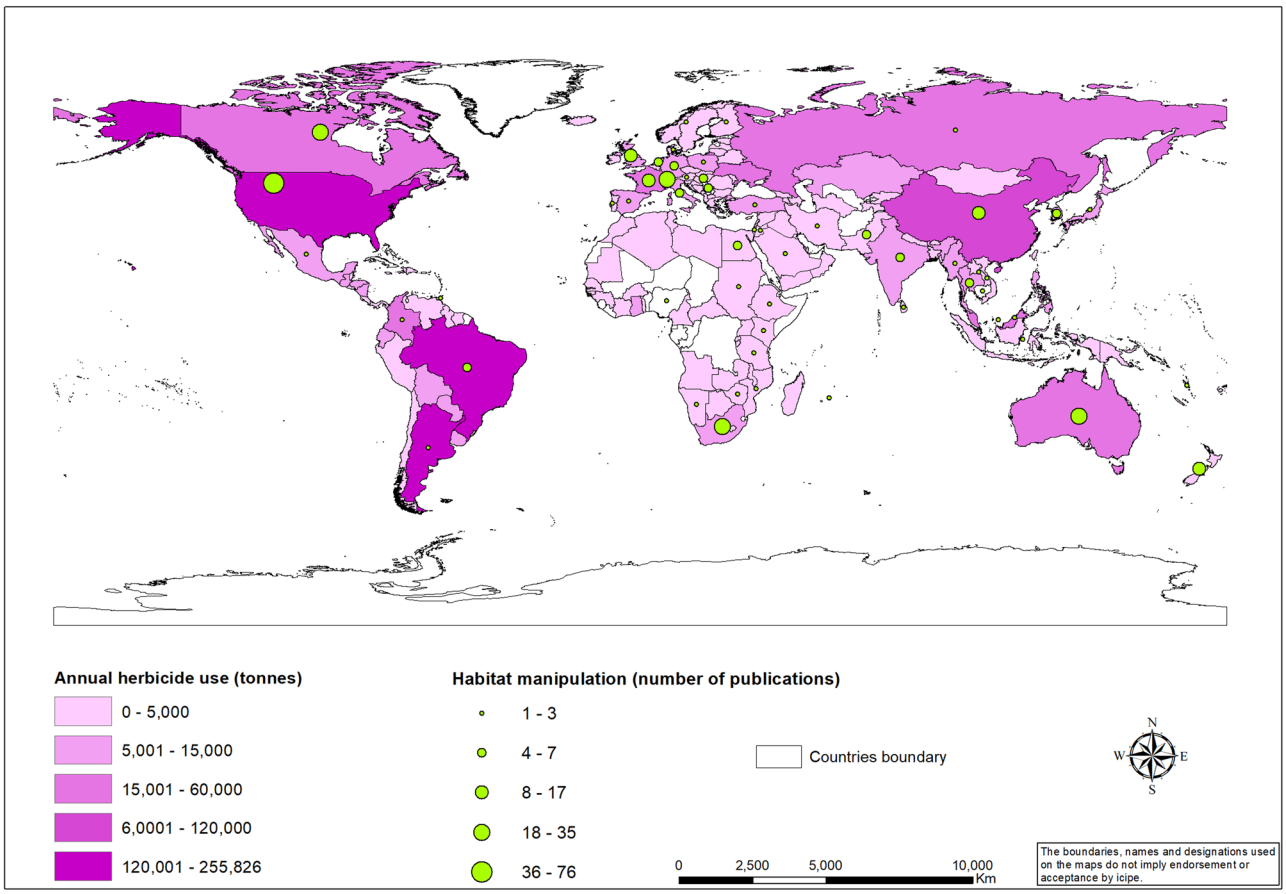


Fig. 2. The global trend in annual herbicide application (tonnes) and habitat manipulation (based on the number of publications) as weed control strategies.

glyphosate and aminomethylphosphonic acid has been recorded in Europe, Australia, and North America regions (Silva et al. 2018, Zhang et al. 2019, Maccario et al. 2022). Such extreme cases are projected to increase, ultimately imperiling the biodiversity and sustainability of agroecosystems.

One of the emerging ecological weed management (EWM) approaches is the manipulation of habitat to augment the ecological pressure induced by natural enemies (Fig. 2). This model seeks to manipulate the weed ecosystem to favor the proliferation of natural herbivores, granivores, and plants with allelopathic properties. Since the inception of classical biological control of weeds, more than 400 arthropod species have been released worldwide, collectively targeting more than 175 weed species. Of these, biological control agents from the orders Coleoptera, Lepidoptera, and Diptera collectively account for over 80% of the releases, with the plant families Asteraceae, Cactaceae, and Fabaceae representing the most frequently targeted taxonomic groups (Schwarzländer et al. 2018, Paynter et al. 2019, Harms et al. 2020, Panta et al. 2024). However, the most puzzling downside of habitat modification and biological control of weeds is the extensive period and resources required to augment the natural enemies to sufficient levels that can adequately suppress weed populations. In addition, most classical biological control programs involve the deliberate release of mass-reared, host-specific natural enemies to suppress invasive weeds considered highly noxious (Schwarzländer et al. 2018). Although this approach can effectively reduce the abundance of target species, numerous ecological theories suggest that the resources and space released following suppression may be exploited by other weed species (Davis et al. 2000, Shea and Chesson 2002, Pearson et al. 2018). If the ecological conditions that promoted the initial invasion remain unchanged, secondary invasion or replacement by other undesirable weeds may occur, resulting in a shift in community composition rather than long-term restoration of the ecosystem.

Shifting from Weed Control to Weed Resource Utilization

Although attaining optimum crop yield requires a stable supply of plant nutrients and management of biotic stress, complete eradication of weeds within agricultural ecosystems is not feasible. This is attributable to the persistence of dormant weed seeds within the soil seed bank, which remain viable and poised to germinate upon onset of favorable environmental conditions. Additionally, new seeds are continuously dispersed into crop fields through natural mechanisms, proving the intricacy of weed density and population dynamics. Collectively, these ecological realities have consigned farmers into a perpetual arms race against weeds, characterized by escalating herbicide reliance and the concurrent evolution of resistant weed biotypes. Nevertheless, we contend that framing weeds exclusively as agronomic liabilities represents an oversimplification that obscures their broader ecological significance. Rather, weed biomass constitutes underutilized resources with considerable potential for multifunctional exploitation across agricultural and allied systems.

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While weeds are frequently documented as highly competitive and responsible for crop yield loss, their diversity is often beneficial to broader ecosystem functioning (Storkey and Westbury 2007, Storkey and Neve 2018, MacLaren et al. 2020, Smith et al. 2020). For instance, previous observations have established that the abundance of weed communities in agricultural landscapes supports a broad range of pollinator species, ultimately enhancing crop production (Bretagnolle and Gaba 2015, Rollin et al. 2016, Balfour and Ratnieks 2022). Weeds also play a vital role in sustaining flagship species and providing seeds for granivores (Biesmeijer et al. 2006, Bretagnolle and Gaba 2015). Furthermore, recent evidence demonstrates that highly diverse weed communities often cause low competition with crops in agroecosystems (MacLaren et al. 2020). For instance, in a study by Adeux et al. (2019), 2 out of the 6 weed communities evaluated did not affect cereal yield, whereas Storkey and Neve (2018) detected a 30% decrease in wheat yield with an increase in weed species richness from 7 to 20 species. Additionally, Cierjacks et al. (2016) and Ferrero et al. (2017) observed a positive correlation between weed diversity and the yields of banana, coconut, and soybeans (Cierjacks et al. 2016, Ferrero et al. 2017). A possible explanation of this trend is that highly diverse weed species often exhibit diverse resource demands, ultimately exhibiting low competition with crops while offering multiple provisioning services. Nevertheless, Ryan et al. (2009) established that organic systems can accommodate up to 6 times the rate of weeds without compromising crop yield, whereas Swanton et al. (2015) noted that weeds emerging post-crop establishment are less competitive compared to those that emerge before crops. Thus, we advocate for integrated management interventions that regulate weed densities and preserve functional diversity, without compromising crop productivity—thereby transforming this purported agronomic burden into a strategically harnessed resource.

Valorization of Weed Biomass Using Edible Insects

Outlook of Edible Insect Farming

Mass production of edible insects (mini-livestock) is emerging as a de novo intervention to overcome food insecurity and meet dietary demands of the growing human population. Insect farming is considered a crucial approach to lessen the growing pressure of food production on the environment and complement the declining supply of animal proteins (Kelemu et al. 2015, Dobermann et al. 2017, Tanga et al. 2021). However, entomophagy is not a novel phenomenon, as previous research indicates that humans consumed insects throughout their evolutionary history, with more than 470 edible insect species documented worldwide (Bequaert 1921, Quin 1959, Raubenheimer and Rothman 2013, Kelemu et al. 2015, Dobermann et al. 2017). Although edible insects are diverse, species consumed most often belong to the order Coleoptera, followed by Hymenoptera, Lepidoptera, Orthoptera, and Hemiptera, which account for 88.2% of edible insect species (Van Huis 2003, Kelemu et al. 2015, Omuse et al. 2024). Other insects from the orders Isoptera, Odonata, Diptera, Dictyoptera, Ephemeroptera, Plecoptera, Trichoptera, Phasmida, Megaloptera, Blattodea, Psocoptera, and Dermaptera constitute 11.8% of edible insect species (Kelemu et al. 2015, Dobermann et al. 2017, Omuse et al. 2024).

Successful farming of edible insects requires a constant supply of feed, which is often low-quality substrates. Edible insects from different orders feed on a wide range of substrates, such as fresh plant materials, decaying plant tissues, decaying carcasses, and excrement (Fig. 3A–D) (Dobermann et al. 2017, Varelas and Langton 2017, Varelas 2019, Pinotti and Ottoboni 2021). For edible insect farming practices to be feasible, the feed substrates must be readily available, accessible, and cost-effective. As such, efforts have been made to domesticate insects that feed on low-value products such as organic wastes to lessen the potential competition for materials currently used for human consumption and livestock feed. For instance, the black soldier fly (BSF) *Hermetia illucens* L. (Diptera: Stratiomyidae) has emerged as the most valuable insect with an exceptional ability to convert organic wastes into high-quality biomass (Chia et al. 2018, 2020, Varelas 2019, Sanjaya et al. 2020, Surendra et al. 2020, Menino et al. 2021, Parodi et al. 2021, Beesigamukama et al. 2023, Megido et al. 2024, Tanga et al. 2026). Edible insects that feed on low-value organic wastes not only serve as cost-friendly sources of high-protein livestock feed but also lessen the environmental concerns of solid wastes, whereas the frass serves as a soil amendment for agricultural applications. A large proportion of edible arthropods feed on fresh herbaceous plants and the decomposing remains of plant materials, whereas only a small fraction feed on carrion (Fig. 3A).

Although organic wastes from urban environments have been widely explored as feedstock for many edible insects in the orders Diptera and Coleoptera, many farmers in rural areas have limited access to such wastes due to low industrialization (Tanga et al. 2021, Megido et al. 2024). The most suitable substrates in such settings are livestock manure, particularly from commercial poultry and pig farming (Shumo et al. 2019, Parodi et al. 2021). However, small-scale livestock production systems which dominate most developing countries often do not generate sufficient quantities of organic wastes to sustain commercial insect farming (Tanga et al. 2021, Megido et al. 2024). To supplement these waste streams, weeds, which are typically regarded as undesirable in agricultural systems, can be utilized as an alternative feed substrate for edible insect production, transforming underutilized biomass into a valuable agricultural resource. Moreover, weeds supply nutrients from plant sources, ensuring balanced nutrition for optimal edible insect growth. Their utilization as a sustainable and low-cost feed resource could provide a key strategy for overcoming feedstock limitation that constrains the adoption and scalability of edible insect farming, particularly in small-scale farming systems (Halloran et al. 2018, Kuo and Fisher 2022).

Weed biomass is a rich source of crude protein (CP), lipid, neutral detergent fiber (NDF), acid detergent fiber (ADF), and other essential nutrients, making it a suitable feedstock for edible insect production (Khan et al. 2013, Schutte and Lauriault 2015). Weeds such as *Cyperus rotundus* Linn. (Poales: Cyperaceae) and *Amaranthus viridis* L. (Caryophyllales: Amaranthaceae) have up to 57.7% ADF, whereas *Phalaris minor* Retz. (Poales: Poaceae) and *Taraxacum officinale* G.H. Weber ex Wiggers (Asterales: Asteraceae) have 34.4% to 38.8% ADF (Fig. 4). This is comparable to ADF levels in crops such as maize, oat, sorghum, and cowpea (26.3% to 40.2%), which are predominantly used as food (Das et al. 2015). Additionally, weeds such as *Rumex crispus* L. (Caryophyllales: Polygonaceae), *A. viridis, Convolvulus arvensis* L. (Solanales:

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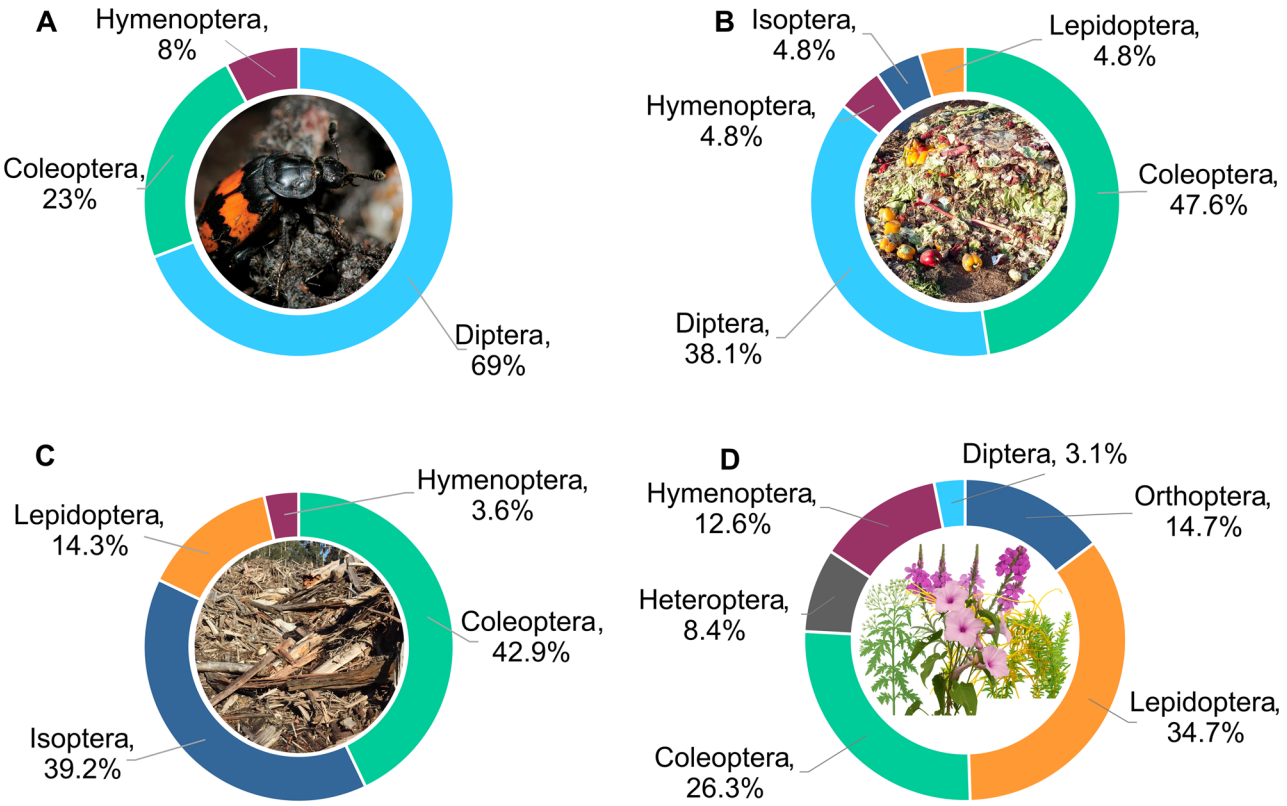


Fig. 3. Edible insects as represented by their order and substrates: carrions (A), decaying plant materials and excrement (B), forest biomass (C), and fresh herbaceous plants (D). Source: Van Huis 2003, Kelemu et al. 2015, Dobermann et al. 2017, Varelas and Langton 2017, Varelas 2019, Pinotti and Ottoboni 2021, Beesigamukama et al. 2023, Megido et al. 2024, Omuse et al. 2024.

Convolvulaceae), and *Medicago polymorpha* L. (Fabales: Fabaceae) have 21.5% to 26.6% CP content, which is also comparable to levels in the aforementioned food crops (Fig. 4) (Khan et al. 2013, Das et al. 2015). Furthermore, weeds such as *Avena fatua* L. (Poales: Poaceae) and *Dichanthium annulatum* Forrsk (Poales: Poaceae) have an exceptionally high crude fiber content of 28.9% to 31.3%, which makes them highly nutritious for edible insects from various families, such as Gryllidae, Acrididae and Tenebrionidae (Khan et al. 2013, Kuo and Fisher 2022, Riekkinen et al. 2022). Recent studies have shown that *Desmodium uncinatum* (Jacq.) DC. (Fabales: Fabaceae) contains high levels of carbohydrates (9.7%) and lipids (68.8%), compared to commercial feeds (Magara et al. 2025). In contrast, *Galinsoga parviflora* Cav. (Asterales: Asteraceae) and *Ipomoea alba* L. (Solanales: Convolvulaceae) exhibited the highest crude fiber and protein contents of 29.3% and 23.5%, respectively (Magara et al. 2025).

Edible insects reared on weed biomass often exhibit enhanced growth performance, characterized by faster development, higher survival rates, and greater weight gain. For instance, crickets fed on weeds from Poaceae, Pontederiaceae, Asteraceae, and Araceae families exhibited a 37% to 100% increase in growth, survival, and weight relative to the reference feed (Fig. 5A and (B) (Miech et al. 2016, Kuo and Fisher 2022, Magara et al. 2025). Further studies have reported 87% to 100% survival of the BSF larvae fed on weeds from the Poaceae, Pontederiaceae, and Asteraceae families, whereas a survival range of 72% to 85% was observed for short-horn grasshoppers and mealworms fed on weeds from the Poaceae and Araceae families (Fig. 5A and Table 2) (Ghosh et al. 2014, Sanjaya et al. 2020). Recent findings have demonstrated acceptance of 48 weed species as feed by the edible cricket *Gryllus madagascarensis* (Walker), with high preference for *Colocasia esculenta* (L.) Schott (Alismatales: Araceae), *Afroamphica africana* (Hook.f.) H. Ohashi & K. Ohashi (Fabales: Fabaceae), *Neonotonia wightii* (Arn.) J.A. Lackey (Fabales: Fabaceae), *G. parviflora*, *I. alba*, and *D. uncinatum* (Magara et al. 2025). In contrast, other studies have reported relatively low survival rates of 5% to 30% for crickets fed on weeds belonging to the families Cleomaceae, Asteraceae, Amaranthaceae, Commelinaceae, and Nyctaginaceae (Fig. 5A) (Choo et al. 2017, Magara et al. 2019, Kuo and Fisher 2022). These variations are likely attributable to differences in weed families, diet formulation, and rearing conditions; thus, further research is needed to optimize weed-based diet formulations and rearing protocols for edible insect production. Harnessing weed resources for edible insect production offers multiple benefits for sustainable agriculture and food systems (Fig. 6).

Crop Yield Benefits of Integrated Weed Management Using Edible Insects

The systematic harvesting of arable weeds mitigates their competitive pressure on crops, reducing biotic stress and consequently improving crop yields (Fig. 6). Weeds differ substantially in their competitive ability, and thus yield loss is almost always associated with the combined effect of multiple weed species (Milberg and Hallgren 2004). Although estimation of crop yield loss due to weed infestation is invaluable for effective control, such evaluations are often intricate, due to the broad dynamics underlying crop-weed competition. For instance,

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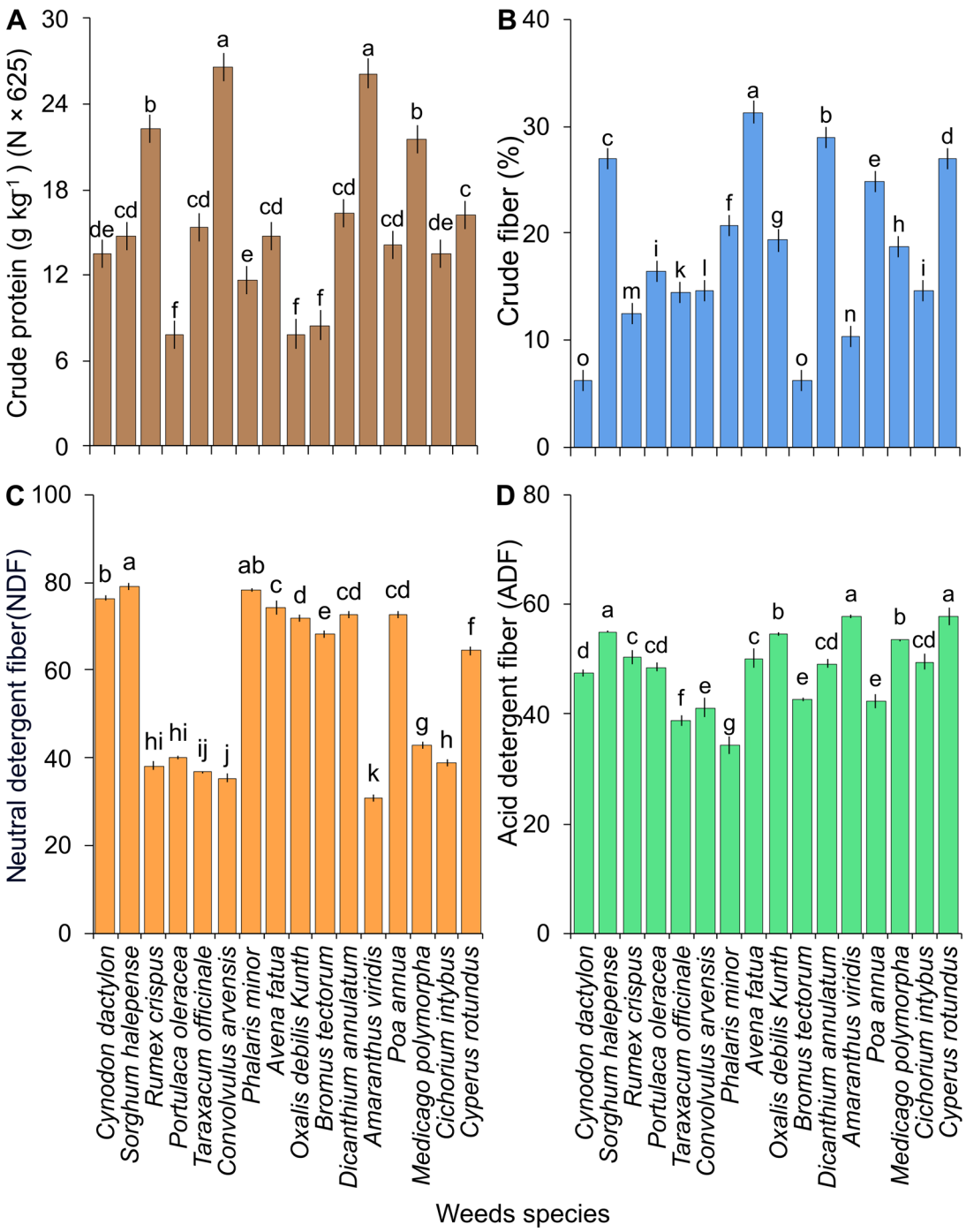


Fig. 4. Percentage proximate composition of various weeds used to feed edible insects: Crude protein (A), crude fiber (B), neutral detergent fiber (C) and acid detergent fiber (D). Sources: Khan et al. 2013, Das et al. 2015, Schutte and Lauriault 2015.

previous studies have revealed that autumn crops have a high competitive ability against weeds compared to spring-sown crops (Kruidhof et al. 2008, Mohler 2009, Tørresen et al. 2020). Nonetheless, certain weed species exude allelochemical compounds, whereas others exhibit autotoxicity that limits the growth of other cultivated crops (Bouhaouel et al. 2015, Möhler et al. 2018, Abbas et al. 2021, Xu et al. 2023). Therefore, the mechanical harvesting of these weeds and their subsequent utilization as feedstock in edible insect production systems lessens weed-induced biotic stress, which translates to increased crop yield and agricultural productivity. However, field-based studies are still needed to evaluate the effect of systematic weed harvesting for insect feed on crop yield, weed regrowth, labor requirements, and farm profitability.

Ecological Benefits and Reduced Herbicide Application

Harnessing weed biomass presents a lucrative solution for eliminating the high cost and detrimental effects of herbicides, promoting healthier agroecosystems (Fig. 6). While herbicides are integral to contemporary food security strategies, their excessive and injudicious application poses significant threats to human health and biodiversity. Previous reports have linked

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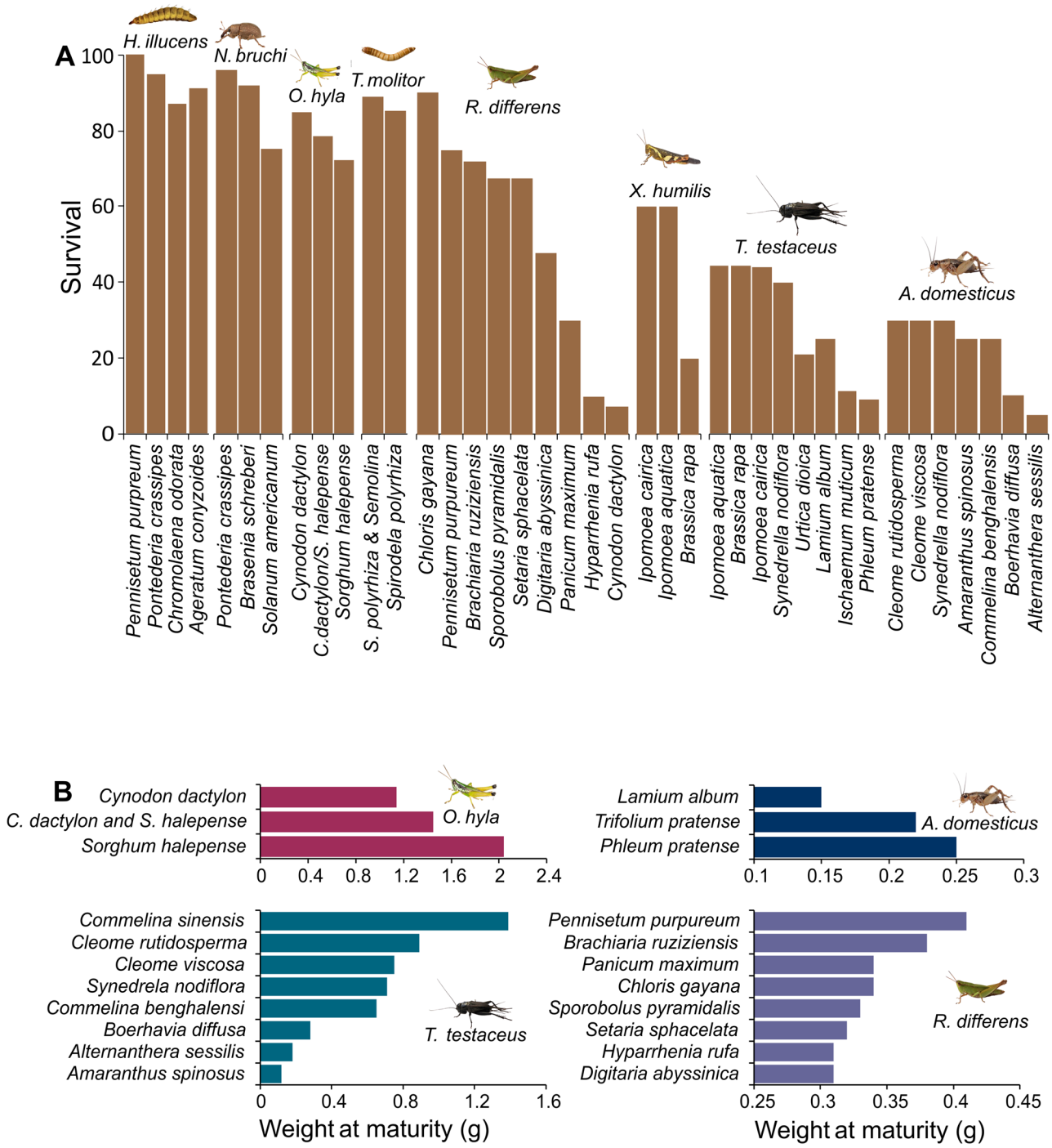


Fig. 5. Survival (A) and weight gain (B) of edible insects fed on common weed species. Source: Ajuonu et al. 2003, Ghosh et al. 2014, Choo et al. 2017, Malinga et al. 2020, Sanjaya et al. 2020, Bordiean et al. 2022, Kuo and Fisher 2022.

pesticide exposure with elevated risks of neurological disorders, respiratory diseases, endocrine disruptions, and various cancers (Tarmure et al. 2020, Schwingl et al. 2021, Jokanović et al. 2023, Tang et al. 2025). Beyond human health, the intensification of agrochemical use has been associated with measurable declines in soil fauna diversity, pollinator abundance, avian populations, and stream macroinvertebrate communities, collectively undermining the structural and functional integrity of agricultural ecosystems (Tang et al. 2025). The ecological ramifications of herbicide application are not confined to the point of use; rather, they cascade across trophic levels and transcend geopolitical boundaries through atmospheric deposition, surface runoff, and trade in contaminated commodities, thereby transgressing foundational principles of environmental sustainability (Tang et al. 2025). Therefore, the bioconversion of mechanically harvested ruderal and invasive weed biomass through edible insect rearing offers a systems-level and environmentally friendly approach to mitigating herbicide dependency, while simultaneously generating high-value insect protein and advancing the transition toward more regenerative and sustainable food production systems (Fig. 6).

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Table 2. Orders, families and species of edible insects and the corresponding species of weeds commonly used as feed

Insect order and family	Insect species	Weed family	Weed species	Reference(s)
Orthoptera: Gryllidae	Crickets (*Acheta domesticus* L., *Gryllus bimaculatus* L, *Teleogryllus mitratus* Burmeister, *Valanga nigricornus* Burmeister, *Xenocatantops humilis* Serville, and *Scapsipedus icipe* Hugel and Tanga)	Asteraceae	Cinderella Weed (*Synedrella nodiflora*)	(Kuo and Fisher 2022)
		Convolvulaceae	Cairo morning glory (*Ipomoea cairica*), Water spinach (*Ipomoea aquatica*) and Invasive *Ipomea hildebrandtii*	(Choo et al. 2017, Kuo and Fisher 2022)
		Cleomaceae	Purple cleome (*Cleome rutidosperma*) and Spiderflower (*Cleome viscosa*)	(Miech et al. 2016)
		Commelinaceae	Wandering Jew (*Commelina* spp.)	(Miech et al. 2016, Ng'ang'a et al. 2020)
		Nyctaginaceae	Red spiderling (*Boerhavia diffusa*)	(Miech et al. 2016)
		Caryophyllaceae	Common gypsophila (*Gypsophila paniculata*)	(Vaga et al. 2020)
		Fabaceae	Red clover (*Phleum pratense*)	(Vaga et al. 2020)
		Lamiaceae	White nettle (*Lamium album*)	(Vaga et al. 2020)
		Poaceae	Centipede grass (*Ischaemum muticum*)	(Choo et al. 2017)
Orthoptera: Acrididae	Grasshoppers (*Melanoplus sanguinipes* Fabricius, *Oedaleonotus enigma* Scudder, *Oxya hyla hyla* Serville, *Melanoplus borealis* Fieber, *Hesperotettix viridis* Thomas, and *Ruspolia differens* Serville)	Asteraceae	Knapweed (*Centaurea diffusa*) and Narrowleaf hawksbeard (*Crepis tectorum*)	(Fielding et al. 1996)
		Convolvulaceae	Cairo morning glory (*Ipomoea cairica*) Water spinach (*Ipomoea aquatica*)	(Choo et al. 2017, Kuo and Fisher 2022)
		Poaceae	Johnson grass (*Sorghum halepense*), Scutch grass (*Cynodon dactylon*), Congo grass (*Brachiaria ruziziensis*), Guinea grass (Panicum maximum), Jaraguá (*Hyparrhenia rufa*), Rhodes grass (*Chloris Gayana*), Giant rat's tail grasses (*Sporobolus pyramidalis*), and Napier grass (*Pennisetum purpureum*), African bristlegrass (*Setaria sphacelata*), and East African couchgrass (*Digitaria abyssinica*)	(Ghosh et al. 2014, Malinga et al. 2020)
		Asteraceae	Snakeweed (*Gutierrezia surothrae*)	(Thompson et al. 1996)
Orthoptera: Cyrtacanthacridinae	Desert locust (*Schistocerca gregaria* Forskal)	Poaceae	Mauritanian grass (*Ampelodesma mauritanica*), Sand couch-grass (*Agropyrum junceum*), Wild oats (*Avena* sp.), Bermuda grass (*Cynodon dactylon*), and Cogon grass (*Imperata cylindrica*)	(Tarai and Doumandji 2009)
Coleoptera: Tenebrionidae	Yellow mealworm (*Tenebrio molitor* L.)	Araceae	Duckweed (*Spirodela polyrhiza*)	(Bordiean et al. 2022)
		Asteraceae	Milk thistle (*Silybum marianum*)	(Toviho et al. 2023)
Coleoptera: Curculionidae	Hyacinth weevil (*Neochetina eichhorniae* Warner and *Neochetina bruchi* Hustache), Stem-boring weevil (*Listronotus setosipennis* Hustache),	Pontederiaceae	Water hyacinth (*Pontederia crassipes*)	(Ajuonu et al. 2003)
		Solanaceae	American black nightshade (*Solanum americanum*)	(Perkins and Maddox 1976)
		Cabombaceae	Watershield (*Brasenia schreberi*)	(Perkins and Maddox 1976)
	Leaf-feeding beetle (*Zygogramma bicolorata* Pallister), and seed-feeding weevil (*Smicronyx lutulentus* Dietz)	Asteraceae	Parthenium weed (*Parthenium hysterophorus*)	(Strathie et al. 2021)
Coleoptera: Chrysomelidae	Tortoise beetle (*Physonota maculiventris* Boheman)	Asteraceae	Mexican sunflower (*Tithonia diversifolia*)	(Mphephu et al. 2017)
Diptera: Stratiomyidae	Black soldier fly (*Hermetia illucens* L.)	Asteraceae	Kirinyuh (*Chromolaena odorata*) and Babadotan (*Ageratum conyzoides*)	(Sanjaya et al. 2020)
		Poaceae	Elephant grass (*Pennisetum purpreum*)	(Sanjaya et al. 2020)
		Pontederiaceae	Water hyacinth (*Pontederia crassipes*)	(Hassan et al. 2023, Vodounnou et al. 2024)

(Continued)

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Table 2. (Continued)

Insect order and family	Insect species	Weed family	Weed species	Reference(s)
Lepidoptera: Saturniidae	Edible Saturniids (*Bunaea alcinoe* Stoll, *Cirina forda* Westwood, *Gonimbrasia cocaulti* Darge and Terral, *Gonimbrasia krucki* Westwood, *Gonimbrasia belina* Westwood, *Gonimbrasia zambesina* Walker, *Gynanisa nigra* Bouvier)	Fabaceae	Acacia nilotica (*Vachellia nilotica*) and Black wattle (*Acacia mearnsii*)	(Kusia et al. 2021)
		Zygophyllaceae	Desert date tree (*Balanites aegyptiaca*)	(Kusia et al. 2021)
		Anacardiaceae	Brazilian peppertree (Schinus terebinthifolia) and Peruvian peppertree (*Schinus molle*)	(Kusia et al. 2021)
Lepidoptera: Tortricidae	Stem-galling moth (*Epiblema strenuana* Walker)	Asteraceae	Parthenium weed (*Parthenium hysterophorus*)	(Shabbir et al. 2019)

Insect Protein Benefits from Weed Biomass Bioconversion

Bioconversion of weed biomass, whether fresh, dried, or decomposed, yields high-value insect protein for livestock feed and human consumption (Fig. 6) (Magara et al. 2025). Insects are rich sources of essential nutrients and, in many cases, contain higher protein and fat contents compared to animal sources, that is, beef, pork and poultry (Rumpold and Schlüter 2013, Tanga and Ekesi 2024). According to previous observations, the Orthoptera clade has the highest protein content (61.3%), followed by Blattodea (57.3%) and Odonata (55.3%) (Rumpold and Schlüter 2013). Other orders such as Diptera, Hemiptera, Hymenoptera, and Lepidoptera have comparable protein contents of 49.5%, 48.35, 46.5%, and 45.4%, respectively (Rumpold and Schlüter 2013). Although Coleoptera and Isoptera clades exhibit relatively low protein contents of 40.7% and 35.3%, these levels are still higher than protein contents in beef, veal, lamb, poultry, pork and mutton (19.3% to 24.8%) (Williams 2007, Pereira and Vicente 2013, Rumpold and Schlüter 2013, Tanga and Ekesi 2024). Additionally, edible insects from the aforementioned clades have higher fat contents ranging from 13.4% to 33.4%, higher than rates in other animal food sources (Rumpold and Schlüter 2013). Notably, the nutrient content of edible insects may vary substantially based on habitat, metamorphic stage, and diet, and such heterogeneities are common even within species. Insect proteins are not only abundant but also highly digestible compared to many plant proteins (Raubenheimer and Rothman 2013, Tanga and Ekesi 2024). As such, they can be valuable sources of digestible protein, especially in low-income countries where up to 85% of protein is derived from plant sources. While previous studies have examined the nutritional composition of insects reared on various feedstocks, including those harvested directly from nature, there is a dearth of focused research on the nutrient profile of edible insects fed exclusively on weeds (Magara et al. 2025).

Soil Health Benefits of Insect-Based Weed Biomass Valorization

Valorization of weed resource into protein-rich biomass also yields frass which can be used as a soil amendment, presenting a fourth win for sustainable production systems (Fig. 6). This circular economy strategy is crucial in recycling nutrients accumulated in weed biomass back into agricultural lands, contributing to sustainable soil health management and crop productivity. Although most arthropods lack inherent enzymatic processes that are essential for degrading fresh plant materials, many have evolved mutualistic relationships with microorganisms such as bacteria and symbiotic protozoa in their guts, which facilitate cellulose digestion (Engel and Moran 2013, Mondal et al. 2023). Due to these mutualistic associations, numerous insects are able to convert organic materials into frass amendments that have multiple soil health benefits. A previous study by Beesigamukama et al. (2022) explored the quality of frass amendment from 9 edible insects (Fig. 7). All the insects were fed on a mixture of agricultural wastes, including wheat bran, brewer's spent grain, potato waste, weeds, and food waste, among others. Overall, frass amendment from the African fruit beetle, *Pachnoda sinuata* Fabricius (Coleoptera: Scarabaeidae) had the highest nutrient content, followed by *H. illucens* and rhinoceros beetle, *Oryctes rhinoceros* L. (Coleoptera: Scarabaeidae), whereas the edible saturniid caterpillar, *Gonimbrasia krucki* Nudaurelia (Lepidoptera: Saturniidae) had the lowest frass quality (Fig. 7). Nonetheless, frass derived from all 9 edible insects exhibited a high fertilizer index, highlighting its potential as a sustainable alternative or supplement to conventional organic fertilizers which are often scarce and costly in low-income countries.

The soil health benefits of frass amendments have been extensively documented (Beesigamukama et al. 2020, Houben et al. 2020, Poveda 2021, Tanga et al. 2022, Anedo et al. 2024, Kisaakye et al. 2024, Onyango et al. 2025). For instance, investigations by Beesigamukama et al. (2020) and Tanga et al. (2022) revealed an increase in maize growth, yield and proximate composition using BSF frass amendments. Similarly, Houben et al. (2020) observed an increase in plant biomass and uptake of nitrogen, phosphorus and potassium in barley using mealworm frass compared to NPK fertilizers. Further studies have revealed a positive correlation between BSF frass application and vegetable yields both in greenhouse and field conditions (Anyega et al. 2021, Chirere et al. 2021, Tan et al. 2021, Abiya et al. 2022, Antoniadis et al. 2023, Beasley et al. 2023, Hénault-Ethier et al. 2023). Barragán-Fonseca et al. (2023) observed an improvement in plant size, flower set, pollination and seeding in *Brassica nigra* (L.) Koch (Brassicales: Brassicaceae) exposed to BSF exuviae under greenhouse conditions. Beyond the provision of soil nutrients, frass obtained from BSF and mealworms has been associated with increased resistance of cruciferous vegetables against pests (Romano et al. 2023, Wantulla et al. 2023, 2024, Chia et al. 2024, Tanga et al. 2026). The BSF frass amendment has also demonstrated nematicidal effects against plant-pathogenic nematodes such as the

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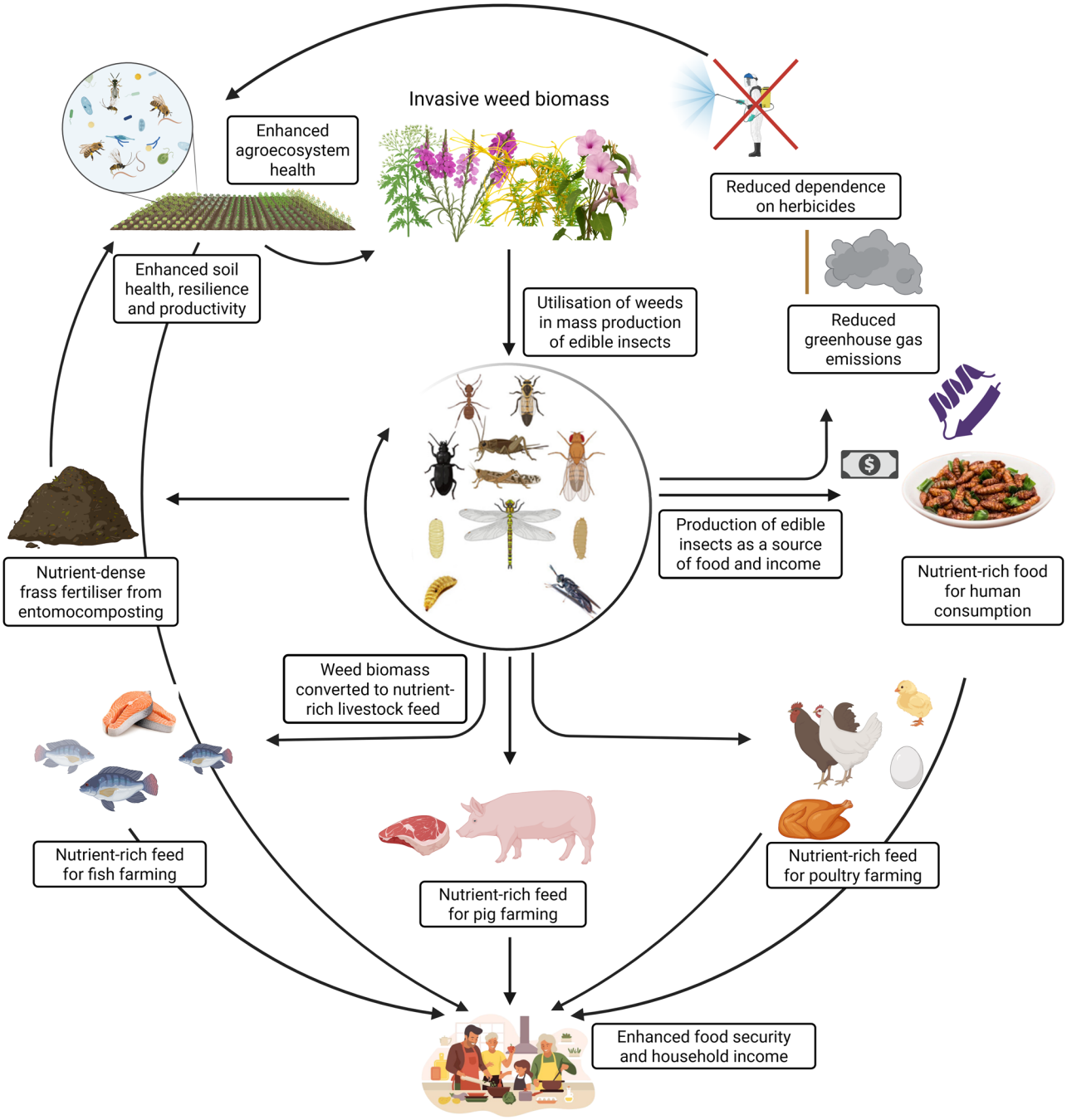


Fig. 6. Circular economic model illustrating the multifaceted benefits of valorizing weed biomass through edible insect farming.

cyst and root-knot nematodes (Anedo et al. 2024, Kisaakye et al. 2024). Further evidence indicates that soils amended with BSF frass exhibit increased microbial abundance, thereby enhancing nutrient availability and use efficiency (Barragán-Fonseca et al. 2022).

Fate of Weed Seedbanks during Entomocomposting

Compared with conventional composting, entomocomposting presents a reliable approach for reducing weed seedbanks persistent in agricultural ecosystems. The process involves harvesting weed biomass before reaching seed set; however, seeds that escape along the harvested biomass are exposed to intense conditions of entomocompositing which reduces their viability. For instance, Meyers et al. (2024) demonstrated that composting with BSF larvae reduced the emergence of *Abutilon theophrasti* Medik. (Malvales: Malvaceae) seedlings by 54%. Previous literature has established that a temperature of 45 °C to 55 °C is sufficient to reduce the viability and germination of seeds of weed species belonging to the families Onagraceae, Asteraceae, Poaceae, Solanaceae, Caryophyllaceae, and Plantaginaceae (Grundy et al. 1998, Larney and Blackshaw 2003, Liu et al. 2020b). During the heap composting process, the mean temperatures may exceed 65 °C, which is sufficient to impair the viability of almost all temperate and tropical weed

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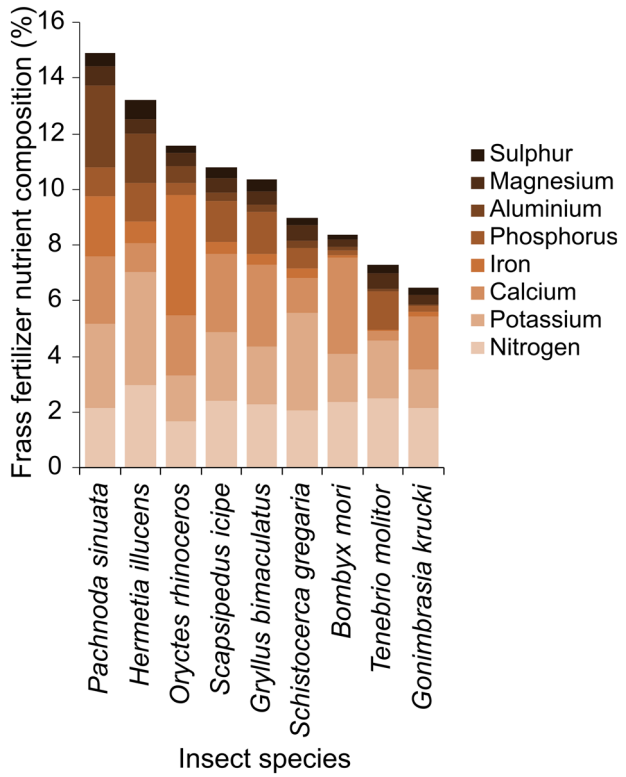


Fig. 7. Nutrient profile of frass fertiliser from entomocomposting using 9 edible insects. Source: Beesigamukama et al. 2022.

seeds. Therefore, entomocomposting using valuable insects such as BSF offers a critical lever for reducing weed seedbanks, limiting subsequent reestablishment in agricultural systems.

Potential of Frass Amendment to Suppress Parasitic Weed Germination

Organic soil amendments may inhibit the germination of various invasive parasitic weeds, such as *Striga hermonthica* (Del.) Benth. For instance, Ayongwa et al. (2011) observed a significant reduction in *S. hermonthica* seed germination following the amendment of the soil with organic matter. Similarly, Gbèhounou et al. (2003) recorded over 50% reduction in germination of *S. hermonthica* over a single rainy season after applying organic manure, whereas a 4-yr experimental study by Tippe et al. (2020) revealed high suppression of the obligate parasite *S. asiatica* in rice fields due to the application of organic amendments. However, Tippe et al. (2020) also observed a disproportionately high survival rate of the facultative parasite *Rhamphicarpa fistulosa* (Hochst.) Benth. (Lamiales: Orobanchaceae) with similar rates of the organic amendment. This calls for further evaluation to establish trade-offs between the management of obligate parasites and the potential of *R. fistulosa* to proliferate under organic soil amendments. Ayongwa et al. (2011) attributed the inhibition of parasitic weed germination to decomposition induced by high organic components. On the contrary, Showemimo et al. (2002) recorded a substantial increase in parasitic weed infestation following the application of organic amendments. These inconsistencies may be attributed to other factors, such as seasonal precipitation and soil properties. Nevertheless, weeds such as *Parthenium* spp., although considered noxious, contain allelopathic compounds that may persist in insect-derived frass following bioconversion, potentially enabling the frass to suppress parasitic weeds in agricultural ecosystems (Bashar et al. 2023). However, deliberate assessments of the impact of frass amendments on the proliferation of parasitic weeds such as *Striga* spp. are required to take this practice forward.

The synthesis of present data on weed infestation challenges conventional wisdom about weed management and has broad policy implications. The key insight from our review is that weeds are responsible for a range of 70% to 100% crop yield loss and are the leading cause of excessive herbicide application. Although herbicide use has the potential to control over 90% of broad-leaf and grass weeds, most herbicides are nonselective and have numerous environmental and public health implications. This could result in a decline of beneficial organisms such as pollinators, natural enemies, and antagonistic microorganisms, undermining the future of crop production. EWM approaches seek to utilize weed densities and biodiversity for economic functions while lessening their impact on crop production. Mass production of edible insects using weeds as feed substrates is a promising intervention with numerous benefits, including the production of high-protein food and livestock feed, ecological weed control, and the production of nutrient-rich organic amendments. By applying ecological principles, the utilization of weeds in the mass production of edible insects can also support the diversity of weeds, which could also benefit pollinators and other mutualistic organisms. Such regenerative and sustainable innovations may reduce the cost of weed management and ultimately increase crop productivity.

Future Research Directions

This blueprint, however, emphasizes the urgent need for ecological research to elucidate the trade-off between the ecological importance of weed diversity in agricultural landscapes and crop yield outputs for farmers. Similarly, a focused evaluation of the toxicity of various weeds—especially those known to be poisonous to larger livestock, like *Parthenium* spp.—is crucial to effectively qualify them as feedstocks for edible insects. Future studies should explore the physiological performance and nutritional composition of various insects fed on a range of weed species, as nutrient contents can vary significantly even among individuals of the same species. While weeds present a promising opportunity for enhancing edible insect farming and bolstering food security, the seasonal nature of many annual weeds may pose a significant challenge. Therefore, it's essential for research to also focus on perennial weeds that thrive year-round, ensuring a more sustainable and reliable resource for insect production. Moreover, it is essential to map the distribution of various weeds across different agro-ecological zones. This information will guide us in identifying the most profitable insect species that can be cultivated in these regions, paving the way for successful and sustainable production. Nonetheless, for integrated management of weeds, judicious use of herbicides is often recommended, some of which may be toxic to farmed insects; therefore, it is vital to assess the safety of weed feedstocks from treated fields for insect production. Lastly, insect farming is still in its infancy, highlighting the urgent need for policies to regulate the use of weeds—previously deemed noxious—as feedstocks for edible insect farming. By transforming these overlooked plants into

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valuable resources, we can pave the way for a more sustainable and innovative food system.

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Author Contributions

Lawrence O. Onyango (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Software [equal], Validation [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), Dennis Beesigamukama (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Resources [equal], Software [equal], Supervision [equal], Validation [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), James W. Muthomi (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Methodology [equal], Supervision [equal], Validation [equal], Writing—review & editing [equal]), Subramanian Sevgan (Conceptualization [equal], Funding acquisition [equal], Methodology [equal], Project administration [equal], Resources [equal], Supervision [equal], Validation [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), and Chrysantus M. Tanga (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Resources [equal], Software [equal], Supervision [equal], Validation [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal])

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Conflicts of Interest

None declared.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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