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Review Article

Carrion-centric insects in plant protection and agroecosystem sustainability: A review

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ABSTRACT

Carrion-centric insects function as vital components in maintaining agroecosystem stability and crop health. This review examines the multifaceted contributions of carrion-centric insects, specifically within the orders Diptera, Coleoptera, and Hymenoptera, as essential drivers of plant protection and soil ecosystem functionality. While these organisms accelerate the decomposition of dead organic mass and facilitate critical nutrient cycling pathways such as nitrogen mineralization and elemental translocation into the rhizosphere, current conservation and agricultural literature remains predominantly vertebrate-centric, leaving a significant gap in the understanding of invertebrate-led crop ecosystem services. This review bridges that gap by establishing an agroecosystem-centered framework that links carrion-centric insect activity directly to soil-rhizosphere health, crop pollination, and sustainable plant protection. The dual functional roles of these insects as non-bee crop pollinators and drivers of specialized soil microbiomes that stimulate systemic acquired resistance against phytopathogens are critically evaluated. Furthermore, the industrial biomanufacturing of insect-derived biopolymers, particularly chitosan and its derivatives, offers a nature-based platform for eco-friendly pest management, seed coatings, and controlled-release biopesticides, replacing traditional synthetic inputs within circular agricultural economies. To ensure biosecure field integration, these agro-ecological services are reconciled with pathogen vector risks through structured spatial management and a One Health biosecurity framework. Aligning insect-centric agroecosystem management with international environmental mandates, such as the Kunming-Montreal Global Biodiversity Framework and UN Sustainable Development Goal 15, is essential for building resilient agricultural landscapes. Ultimately, incorporating carrion-centric insects into modern plant protection strategies provides an indispensable foundation for sustainable crop health, biological pest suppression, and long-term agroecological resilience.

Keywords: Agroecosystem health; Crop pollination; Insect-derived biopolymers; Plant protection; Rhizosphere microbiome; Sustainable agriculture

1. Introduction

Terrestrial and agricultural ecosystems experience dynamic temporal shifts in climatic conditions, directly influencing the competitive capacity of organismal groups to utilize nutrient-dense ephemeral resources. These environmental variations necessitate continuous shifts in the functional composition and population dynamics of scavenger communities. Decomposition of dead organic matter is primarily executed by soil-dwelling organisms with minimal attraction of external fauna (Raw, 1967), positioning invertebrates as the fundamental drivers of carcass breakdown (Cragg, 1955). Despite pervasive ecological pressures across human-modified landscapes, scavengers represent the largest species diversity among insect taxa (Figure 1) (Southwood, 1973). These insects perform a pivotal function in the complete breakdown of animal biomass, facilitating fundamental nutrient cycling pathways within natural and agricultural systems (Shrivastava et al., 2022).

Throughout the multi-stage decomposition process, carcasses undergo sequential physical, biological, and chemical changes. Insects serve as primary agents of disintegration because they possess an elevated degree of structural and functional organization, underpinned by specialized morphology, adaptive physiology, acute sensory capabilities, and complex behavioral traits. Driven by energetic trade-offs, a diverse assemblage of carrion-centric insects across multiple orders including Diptera, Coleoptera, Hymenoptera, Orthoptera, Heteroptera, and Collembola is rapidly recruited to decomposing mass (Shrivastava et al., 2022). While specific species utilize carcass tissue directly as a primary substrate for oviposition and larval development, predator and parasitoid species

are attracted to the dense aggregations of colonizing insects, utilizing them as a transient food resource (Coe & Curran, 1980).

As global anthropogenic pressures and population growth bridge the divide between living systems and inanimate matter, the multifaceted roles of these carrion feeders across agriculture, environmental health, and circular economic frameworks become increasingly vital (Figure 2). However, existing ecological literature remains predominantly vertebrate-centric, often neglecting the molecular, biochemical, and agricultural utility of carrion-centric invertebrates. A significant theoretical gap exists in bridging the functional ecology of carrion-centric insects with modern plant protection paradigms and circular agricultural economies. Moreover, an ongoing controversy persists regarding how to balance the clear agro-ecological benefits of these insects against their potential to act as vectors of animal and plant pathogens under changing climatic regimes.

Within managed agroecosystems, the ecological contributions of carrion-centric invertebrates extend far beyond basic waste removal. The localized breakdown of organic remains by carrion-centric insects alters soil chemical properties, releasing high concentrations of bioavailable nitrogen, phosphorus, and microbial volatile organic compounds. This organic enrichment fuels specialized soil microbiomes that enhance plant health, stimulate systemic acquired resistance against phytopathogens, and improve crop stress tolerance (Hawlena et al., 2012; Wardle et al., 2004). Furthermore, many carrion-centric flies double as essential non-bee pollinators for critical economic crops (Rader et al., 2020), while biopolymers such as chitin and chitosan extracted from insect biomass offer scalable, nature-based alternatives to synthetic agrochemicals for crop pest suppression (Abenaim & Conti, 2023).

This review addresses these critical knowledge gaps by evaluating the core biological functions of carrion-centric insects within the context of sustainable agriculture, plant protection, and international policy frameworks. Specifically, this paper examines how carrion-centric insect life cycles drive crop pollination, soil nutrient translocation, biological pest management, and green biomanufacturing. By integrating these invertebrate-mediated processes into modern plant protection and conservation strategies, this synthesis demonstrates that carrion-centric insects provide an indispensable foundation for resilient agroecosystems and sustainable societal development.

2. Literature Search Strategy and Curation Methodology

To build an agroecosystem-centered narrative synthesis and unified conceptual framework, literature was systematically gathered, curated, and evaluated across major international scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar. The search strategy employed targeted combinations of Boolean operators (AND/OR) and primary keywords, including: carrion-centric insects, necrophagous insects, plant protection, rhizosphere health, soil nutrient cycling, chitosan biopolymers, non-bee crop pollinators, induced systemic resistance, and agroecosystem sustainability.

Literature was evaluated based on strict conceptual inclusion and exclusion criteria. Studies were included if they provided empirical or theoretical evidence directly linking insect activity, biopolymers, pollination, or decomposition directly to crop health, rhizosphere dynamics, and sustainable agricultural management. Conversely, papers limited strictly to forensic timelines, post-mortem intervals, or non-agricultural clinical applications were excluded to maintain a sharp focus on plant protection science. Selected peer-reviewed research articles, scientific monographs, and strategic policy documents were critically synthesized to construct the agroecological framework.

3. Insect Roles in Managed Crop Pollination

Pollinators facilitate a vital ecosystem service by enhancing or stabilizing the yields of approximately 75% of global crop species, with dipterans emerging as critical pollinators across diverse agricultural and botanical landscapes. Despite their ubiquitous presence and extreme abundance, the specific contribution of carrion-centric flies to managed pollination systems and integrated plant protection frameworks is frequently underestimated (Shrivastava et al., 2023). Within this group, three primary families Calliphoridae, Rhiniidae, and Syrphidae represent the most frequently documented taxa visiting agricultural blossoms. A quantitative meta-analysis evaluating 39 global pollination studies identified syrphids and calliphorids as the two most significant non-bee pollinator taxa worldwide (Rader et al., 2020).

Representatives of the genus *Chrysomya*, specifically the hairy maggot blow fly (*Chrysomya rufifacies* (Macquart)) and the small hairy maggot blowfly (*C. varipes* (Macquart)), exhibit extensive geographic distributions and possess a notably high active thermal range (Nelson et al., 2009; Wallman et al., 2005). Endemic species with significant potential for managed crop pollination include the Western Australian bluebottle (*Calliphora dubia* (Macquart)), the carrion breeding blowfly (*C. albifrontalis* Malloch), and the bluebottle fly (*C. varifrons* Malloch). Furthermore, the bluebottle fly *C. vicina* Robineau-Desvoidy serves as an efficient pollinator of Spanish moon trefoil (*Medicago citrina* (Font Quer) Greuter), a wild relative of lucerne (Pérez-Bañón et al., 2003). Due to its cosmopolitan distribution and the ease with which it can be mass reared, *C. vicina* represents a prime candidate for deployment in managed commercial pollination systems (Howlett, 2012).

In the Tri-State region of Australia, blow flies are documented as the most frequent visitors to avocado blossoms and function as the dominant pollinators for this high-value crop (Evans et al., 2011; Vithanage, 1986). Within broader Australian agroecosystems, several *Calliphora* species and the Oriental latrine fly (*C. megacephala* (Fabricius)) are essential to commercial mango production, particularly across the Northern Territory (Anderson et al., 1982). Key dipteran species identified in these agricultural roles include *C. vicina*, the brown blowfly (*C. stygia* (Fabricius)), the lesser brown blowfly (*C. augur* (Fabricius)), and *C. rufifacies* (Howlett et al., 2017). Similarly, in Southern Mexico and Central America, where avocados originate, *C. megacephala* and

related *Chrysomya* species contribute substantially to crop pollination success (Perez-Balam et al., 2012).

Field investigations in Israel demonstrate that the calliphorid hairy maggot blow fly (*C. albiceps* (Wiedemann)) and the common green bottle fly *Lucilia sericata* (Meigen), alongside the housefly (*Musca domestica* Linnaeus), perform significant roles in commercial mango pollination (Dag & Gazit, 2000). In Thailand, females of the carrion-centric blow fly *C. pinguis* (Walker), the oriental latrine fly *C. chani* Kurahashi, and the hairy maggot *C. villeneuvi* Patton are identified as primary pollinators of *Rhizanthes zippelii* (Blume) Spach (Rafflesiaceae) (Banziger, 1996). Additional evidence from New Zealand establishes *C. vicina* as an effective pollinator for hybrid carrot (*Daucus carota* Linnaeus) seed production (Howlett, 2012). In the tropical climate of Hainan Island, China, several blow fly species including *C. megacephala*, *Isomyia* species, *Pierretia* species, *Hemipyrellia* species, and *C. rufifacies* represent the most frequent floral visitors to climbing bridelia (*Bridelia stipularis* (Linnaeus) Blume) and *Cleistanthus sumatranus* (Miquel) Müller Argoviensis (Li et al., 2014). Females within the genera *Lucilia* and *Chrysomya* serve as major pollinators for the corpse flower (*Rafflesia pricei* Meijer) in northern Borneo, Malaysia (Beaman et al., 1988), while syrphid flies are documented as regular floral visitors across various New Zealand plant species within the families Onagraceae, Asteraceae, and Rosaceae (Primack, 1978).

4. Nutrient Cycling and Ecosystem Contributions

Carrion functions as a fundamental ecological catalyst in terrestrial and agricultural ecosystems, providing diverse organisms with vital nutrient resources, arenas for courtship, reproductive substrates, and temporary refugia. Consequently, the ecological benefits derived from carcass decomposition extend far beyond strictly carrion-centric species (Baz et al., 2010). Ecological dynamics are further complexified by widespread omnivory, as numerous species frequently forage outside their primary trophic classifications (Richardson et al., 2012). While the role of carrion-centric insects in the direct consumption and physical fragmentation of carrion is well documented, their broader influence on the subsequent translocation of essential nutrients into underlying soils and floral biomass represents a pivotal pathway of nutrient recycling for sustainable crop production (Barton et al., 2013; Parmenter & MacMahon, 2009; Wilson & Wolkovich, 2011).

Carrion eaters demonstrate exceptional efficiency at sequestering and converting dead organic matter, thereby actively shaping ecosystem structure and functional integrity. The carcasses of large herbivores introduce substantial, ephemeral pulses of energy and concentrated nutrients into terrestrial food webs. The rapid biological recycling of these organic materials is a critical process that regulates nutrient availability and soil metabolic dynamics on a global scale (DeAngelis et al., 1989).

Due to their ecological dominance across ecosystems, ant species that have evolutionarily adopted collective foraging gain a distinct advantage in efficiently discovering and exploiting such resources, as documented across diverse systems (Oliveira-Santos et al., 2022). For example, twelve of twenty-five sampled ant species were reported feeding on avian carrion due to their broad, generalist diets. Furthermore, the forest canopy and ground layers are frequently shared by both arboreal and ground-dwelling ant communities (Antoniazzi et al., 2020; Dejean et al., 2019). Ground-dwelling ants often climb trees during foraging activities, a phenomenon observed even within Mediterranean ecosystems (Martinez, 2015). Arboreal ants similarly exhibit frequent vertical movement between the ground and canopy strata (Hashimoto et al., 2010).

Other insect taxa, particularly beetles and flies, play an equally essential role in the decomposition process of avian corpses, with their functional importance increasing markedly during the warm season (Anderson, 2019; Eubanks et al., 2019; Merritt & De Jong, 2015). Furthermore, behavioral traits in specific taxa contribute directly to localized soil enrichment. In the case of the burying beetle *Nicrophorus orbicollis* (Say), specific behaviors play a key role in releasing carrion nutrients directly into the soil by sequestering carrion resources within the immediate ecosystem where they were deposited (Woelber-Kastner et al., 2021).

The quantitative biogeochemical impact of decaying vertebrate remains is equally profound across agricultural landscapes. Research indicates that a single 30 kg kangaroo carcass contributes the equivalent of 4.4 kg N/m² to the underlying soil profile (Macdonald et al., 2014). Given that the phosphorus content of an average vertebrate carcass is approximately one third that of its total nitrogen content, such organic remains provide a substantial, localized phosphorus influx to surrounding vegetation (Carter et al., 2006). Indeed, a 30 kg kangaroo carcass can release up to 1.4 kg P/m² into the rhizosphere (Barton et al., 2016).

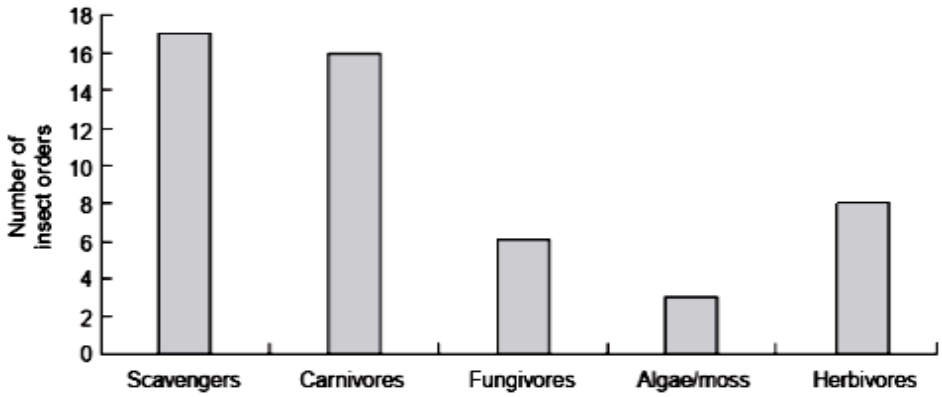

Figure 1. Major feeding guilds of insects categorized by total order diversity (Southwood, 1973).

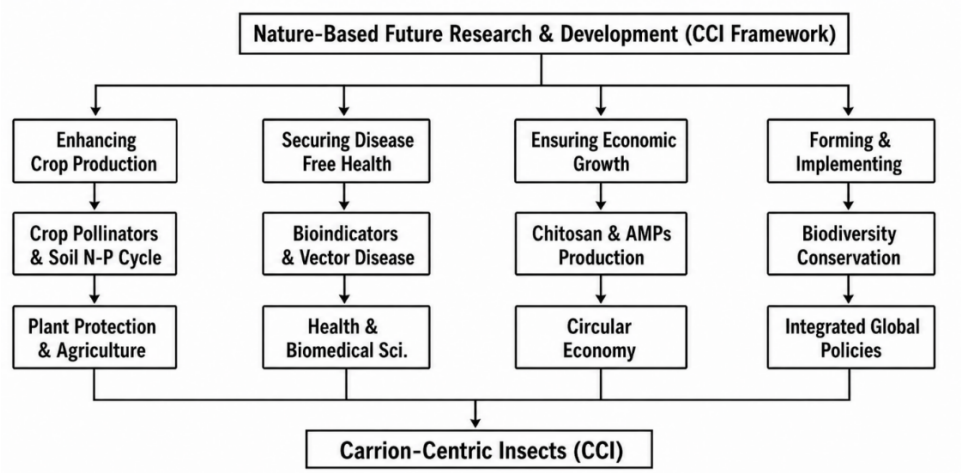

Figure 2. Strategic conceptual framework illustrating the nature-based research and development applications of Carrion-Centric Insects (CCI). The overarching CCI framework cascades into four primary domains: (i) Enhancing crop production, driven by non-bee crop pollinators and insect-mediated soil nitrogen-phosphorus (N-P) flux in plant protection and sustainable agriculture; (ii) Securing disease-free health, integrating carrion-centric insects as bioindicators and disease vector management within health and biomedical sciences; (iii) Ensuring economic growth, leveraging high-value industrial biomass such as chitosan biopolymers and antimicrobial peptides (AMPs) to foster circular bio-economy models; and (iv) Policy implementation, aligning invertebrate-centric biodiversity conservation with integrated global policy frameworks (e.g., Kunming-Montreal GBF Target 11 and UN SDG 15).

This localized nutrient enrichment is mirrored in the bio-architectural structures constructed by social insects. Termite nests exhibit significantly higher concentrations of available phosphorus and potassium (P_2O_5, K_2O), exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), and elevated microbial activity compared to adjacent uninhabited control soils (Czerwiński et al., 1971). A comparable pattern of nutrient concentration occurs in the soil mounds built by the red imported fire ant *Solenopsis invicta* Buren (Lockaby & Adams, 1985).

Although animal biomass constitutes a small fraction of total terrestrial organic matter, accounting for roughly 0.02% in tropical rainforest ecosystems with less than 10% of that total originating from vertebrates, the invertebrate component is overwhelmingly dominant (Fittkau & Klinge, 1973). Invertebrates comprise approximately 95% of total animal biomass, with nearly 50% of this biological mass residing below the soil surface (Fierer et al., 2009; Odum, 1970). Because invertebrates typically possess shorter lifespans, accelerated maturation rates, and multivoltine reproductive strategies, their annual production of necromass significantly exceeds that of vertebrate species.

Carcasses represent an exceptionally high quality nutrient pulse requiring minimal energy expenditure for acquisition, as they lack the defensive or evasive behavioral capabilities of living prey (Wilson & Wolkovich, 2011). However, the efficiency and continuity of this fundamental nutrient cycle are increasingly threatened by synthetic agricultural contaminants, including veterinary pharmaceutical residues and synthetic chemical pesticides, which exert broad environmental toxicity across scavenger communities. Despite these recognized ecotoxicological risks, a critical lack of standardized statistical data from regulatory bodies regarding the actual exposure rates of non-target carrion feeder insects to these agrochemical contaminants persists (Ruiz-Suárez et al., 2015).

5. Microbial-Assisted Roles for Plant Protection

The microbial decomposition of carrion exerts profound effects on soil microbial communities, nutrient transformation pathways, and plant succession patterns within complex aboveground and belowground biotic networks (Hawlena et al., 2012; Wardle et al., 2004). More than 50% of net primary productivity in specific ecosystems supports substantial herbivore populations (Wardle et al., 2004). Microbial assemblages associated with decaying carcasses continuously modify resource quality, generating specialized insect-derived substrates utilized by microbes to synthesize diverse microbial volatile organic compounds (Boumba et al., 2012). Pathogen avoidance strategies are evident in social insect colonies, such as Western honey bees (*Apis mellifera* Linnaeus) rejecting infected nestmates (Wilson-Rich et al., 2009), as well as insects producing exocrine secretions rich in potent antimicrobial compounds (Nigam et al., 2006; Rozen et al., 2008). Given the massive scale of herbivorous mammal mortality reported across global biomes, these mortality events significantly impact insect populations (Houston, 1985). Ultimately, carrion disintegration directly enhances plant protection by stimulating specialized rhizosphere microbiomes through the discharge of nutrient-rich fluids and volatile organic compounds, which attract beneficial microbes, enhance nutrient bioavailability, and trigger endogenous plant defenses against soilborne phytopathogens.

Close ecological associations between insects and bacteria facilitate active horizontal gene transfer mechanisms (Poole & Crippen, 2009). Although bacterial evolution via horizontal gene acquisition enhances survival capabilities across variable environments, the potential dissemination of antibiotic resistance genes presents biosecurity challenges for animal health. Diverse arthropods including crickets, grasshoppers, cockroaches, and beetles harbor massive gut bacterial concentrations

ranging from 10^6 to 10^{12} colony forming units per milliliter (Cazemier et al., 1997). These resident microorganisms modulate host immune responses, alter host behavior, and influence reproductive performance. Activation of the innate immune response can exert pleiotropic effects that suppress insect developmental processes (Ye et al., 2009).

Trade-offs between reproduction and survival are clearly demonstrated in the yellow mealworm beetle (*Tenebrio molitor* Linnaeus), which exhibits reduced phenol oxidase levels in the presence of juvenile hormone inhibitors (Rolff & Siva-Jothy, 2002). Bacterial endosymbionts such as *Wolbachia* species in *Drosophila* enhance host fecundity, whereas whiteflies (*Bemisia tabaci* (Gennadius)) infected with *Rickettsia* sp. nr. *bellii* produce nearly double the number of adult offspring over their lifespan compared to uninfected cohorts (Himler et al., 2011; Libersat et al., 2009). Suppressed bacterial proliferation combined with elevated immune activity has been shown to extend longevity in *Drosophila* species (Linder et al., 2008). Complex interactions between behavior and immunity frequently involve host alterations induced by parasitoids (Libersat et al., 2009). For example, larvae of the ranchman's tiger moth (*Platyprepia virginalis* (Boisduval)) parasitized by the tachinid fly *Thelaira americana* Brooks exhibit dietary shifts, achieving higher survival rates when feeding on poison hemlock rather than lupine (Karban & English-Loeb, 1997). Nevertheless, the physiological costs of mounting immune responses against microbial invaders can yield either positive or negative net fitness impacts on the host organism (Shirasu-Hiza & Schneider, 2007).

In social hymenopterans, worker honey bees (*A. mellifera*) synthesize elevated levels of antibiotic secretions and actively remove waste, dead adult corpses, and larvae parasitized by *Varroa destructor* Anderson and Trueman or *V. jacobsoni* Oudemans mites (Hart & Ratnieks, 2001; Rosengaus et al., 2000). Specific bacterial taxa present in larval diets exert differential effects on dipteran development. In stable flies (*Stomoxys calcitrans* (Linnaeus)), diet supplementation with *Citrobacter freundii* or *Serratia marcescens* accelerates larval development rates (Romero et al., 2006). Conversely, houseflies (*M. domestica*) feeding on colonies of *Escherichia coli* O157:H7 or *Providencia* species display delayed development and smaller adult body size (Ahmad et al., 2006).

Insects actively manipulate surrounding environmental microbial communities by driving competitive interactions between bacterial and fungal populations. For instance, proliferation of the bacterium *Klebsiella oxytoca* exerts detrimental effects on *M. domestica* egg viability and subsequent larval development on ephemeral carrion substrates (Lam et al., 2010). Because fungal colonization on carcasses can severely impede carrion beetle growth (Suzuki, 2001), burying beetles have evolved specialized antimicrobial secretions to suppress fungal growth on breeding substrates designated for larval provisioning (Hoback et al., 2004; Rozen et al., 2008). Mating behaviors are similarly conditioned by microbial immune challenges, as parasitized male crickets cease acoustic calling signals, while females selectively mate only with males demonstrating robust immune encapsulation capabilities (Fedorka et al., 2004).

Although further empirical research investigating interkingdom relationships between microbes and insects remains imperative, these cross-domain ecological interactions represent fundamental drivers governing the broader role of carrion decomposition in plant protection and ecosystem sustainability. As a nutrient-rich resource with high turnover rates, carrion forms an important resource pulse in many ecosystems, though its decomposition rate depends on the composition of carrion-centric insect assemblages (Bump et al., 2009). Pechal et al. (2013) summarized several factors influencing microbial community assembly and function during vertebrate carrion decomposition. Newsome et al. (2021) recently suggested a multi-taxa analysis of microbe, insect, and vertebrate taxa to determine ecological indicators for examining key ecological processes. Benbow et al. (2019) stated that its integration with plant-derived research will improve our understanding of the ecological processes of organic matter inhabiting organisms and their contribution to whole-ecosystem functioning.

6. Contribution Towards Sustainable Ecosystems

Ecological systems are defined by seven fundamental structural and functional attributes that govern their overall operational integrity. These attributes encompass hierarchical organization across trophic chains, open continuous exchanges of matter and energy, and dynamic mechanisms of ecological resistance and resilience essential for maintaining ecosystem homeostasis (Gómez-Márquez, 2023). Within this structural paradigm, carrion functions as an exceptionally high-density nutrient pulse that undergoes decomposition at significantly accelerated rates compared to recalcitrant plant detritus. Consequently, the localized contribution of decaying carcasses to soil fertility maintenance and nutrient cycling is disproportionately massive relative to total carcass biomass (Barton et al., 2013; Swift et al., 1979).

In terrestrial ecosystems, in addition to providing direct and indirect trophic resources, carrion-centric insects and carcass decomposition facilitate the availability of essential non-trophic resources, such as keratinaceous hair and feathers. These structural materials are widely harvested for nest construction by avian taxa, particularly species within the family Paridae (Ondrušová & Adamík, 2013; Pollock et al., 2021) and Corvidae, such as the carrion crow (Bolopo et al., 2015), as well as mammalian species including the garden dormouse (Gil-Delgado et al., 2010). The incorporation of hair and feathers into nest structures directly influences avian reproductive success through diverse mechanisms ranging from enhanced thermal insulation (Perez et al., 2020) to pathogen suppression and disease prevention in nestlings (Aubrecht et al., 2013), as well as mediating sexual selection processes (García-López de Hierro et al., 2013). Consequently, carnivore carrion serves as a vital model to explore the non-scavenging functions of carcasses within ecosystems. Investigating these non-scavenging roles advances our broader understanding of ecosystem dynamics, yielding critical insights into the trophic and reproductive ecology of diverse vertebrate species, where foraging and nesting

behaviors operate as largely independent ecological mechanisms.

The ecological prominence and functional dominance of specific carrion-centric insect taxa within a community can be quantitatively evaluated using the Importance Value Index (IVI). Research demonstrates high IVI values across several key carrion-centric dipterans, including the oriental latrine fly *C. megacephala* (Dossey, 2010; Rozen et al., 2008), the housefly *M. domestica* (Carter et al., 2006), the hairy maggot blow fly *C. rufifacies* (Bocock, 1963; Shrivastava et al., 2017), and various flesh fly species within the genus *Sarcophaga* (Baz et al., 2010; Wang & Wang, 2016). These elevated quantitative metrics indicate that carrion-centric dipterans are not merely passive agents of organic decay but also function as vital bioindicators for monitoring terrestrial ecosystems co-contaminated with potentially toxic heavy metal elements, specifically cadmium (Cd), zinc (Zn), lead (Pb), chromium (Cr), copper (Cu), and nickel (Ni) (Moophayak et al., 2024).

Sustainable ecosystem functioning depends upon an intricate web of biotic interactions, spanning antagonistic trophic consumption to obligate or facultative mutualisms. Because animal mortality occurs stochastically across spatial and temporal scales, a carcass provides an ephemeral yet highly concentrated resource patch for a wide diversity of obligate scavengers, opportunistic consumers, and surrounding flora. Consumers exploiting this transient necromass frequently exhibit pronounced functional responses, including adaptive behavioral foraging shifts and rapid numerical population increases. By facilitating the rapid release of concentrated chemical energy and bioavailable nutrients into surrounding soil and plant communities, carrion-centric insects actively modulate the spatial distribution of diverse organisms, thereby enhancing broader ecosystem biodiversity, food web stability, and functional resilience (Carter et al., 2006; Cortés-Avizanda et al., 2009).

7. Industrial Applications of Carrion-Centric Insects in Green Agriculture

The economic potential of chitin and its biopolymer derivatives in sustainable agriculture is substantial. Market estimates valued the global trade for chitin and related biopolymers at 2,900 million US dollars in 2017, expanding at a compound annual growth rate of 14.8% to reach an estimated 63 billion US dollars by 2024 (Joseph et al., 2021). Major global commercial enterprises including Chinova Bioworks, Heppe Medical Chitosan GmbH, Golden Shell Biochemical, and G.T.C. Bio Corporation actively manufacture a wide array of functional biopolymer products for food preservation, pharmaceutical delivery, agricultural formulations, textile processing, and wastewater treatment industries.

Although approximately 80% of the current commercial biopolymer supply is extracted from marine crustacean shells, transitioning toward carrion-centric insect-derived chitosan represents a transformative advancement within circular agricultural economies (Table 1). Traditional marine derived chitin relies heavily on seasonal bycatch from marine fisheries, presenting inherent supply instability and potential heavy metal contamination risks. In contrast, carrion-centric insect production can be completely standardized within closed-loop automated bio-factories year-round. This circular economic framework minimizes environmental footprints by converting organic agricultural side streams and waste biomass into high-value insect body mass, yielding a scalable, sustainable, and technically superior source of biopolymers for modern plant protection inputs (Philibert et al., 2017).

Table 1. Comparative physicochemical characteristics, advantages, and economic feasibility of crustacean-derived versus insect-derived biopolymers within circular agricultural frameworks.

Parameter / feature	Crustacean-derived biopolymers (traditional)	Insect-derived biopolymers (circular economy)
Tissue source	Exoskeletons containing 6.0% to 25.0% chitin by weight	Cuticular exoskeletons containing 1.2% to 60.0% chitin by dry weight
Crystalline form	α-Chitin	γ-Chitin
Crystallinity (%)	Shrimp shells: 60% to 80%; Crab shells: 70% to 90%	Insects (e.g., cockroaches): 50% to 70%; Silkworms: 60% to 75%
Molecular weight (kDa)	Shrimp shells: 100 to 300 kDa; Crab shells: 150 to 400 kDa	Insects (e.g., cockroaches): 50 to 200 kDa; Silkworms: 100 to 300 kDa
Chemical purity (%)	Shrimp shells: 85% to 95%; Crab shells: 90% to 95%	Insects (e.g., cockroaches): 80% to 90%; Silkworms: 85% to 95%
Source stability & supply	Seasonal availability dependent on marine fishery bycatch	Year round continuous production in automated bio-factories
Environmental footprint	High impact through marine depletion and heavy metal risks	Low impact through organic waste conversion into valuable inputs
Processing requirements	High mineral content requiring harsh demineralization	Lower mineral content enabling milder and cleaner extraction
Key technical advantages	Abundant marine supply, high molecular weight, established methods	Highly renewable, easy to cultivate, high purity, closed-loop sustainability
Primary limitations	Harsh chemical extraction causes environmental drawbacks	Lower initial chitin content requiring optimized extraction protocols

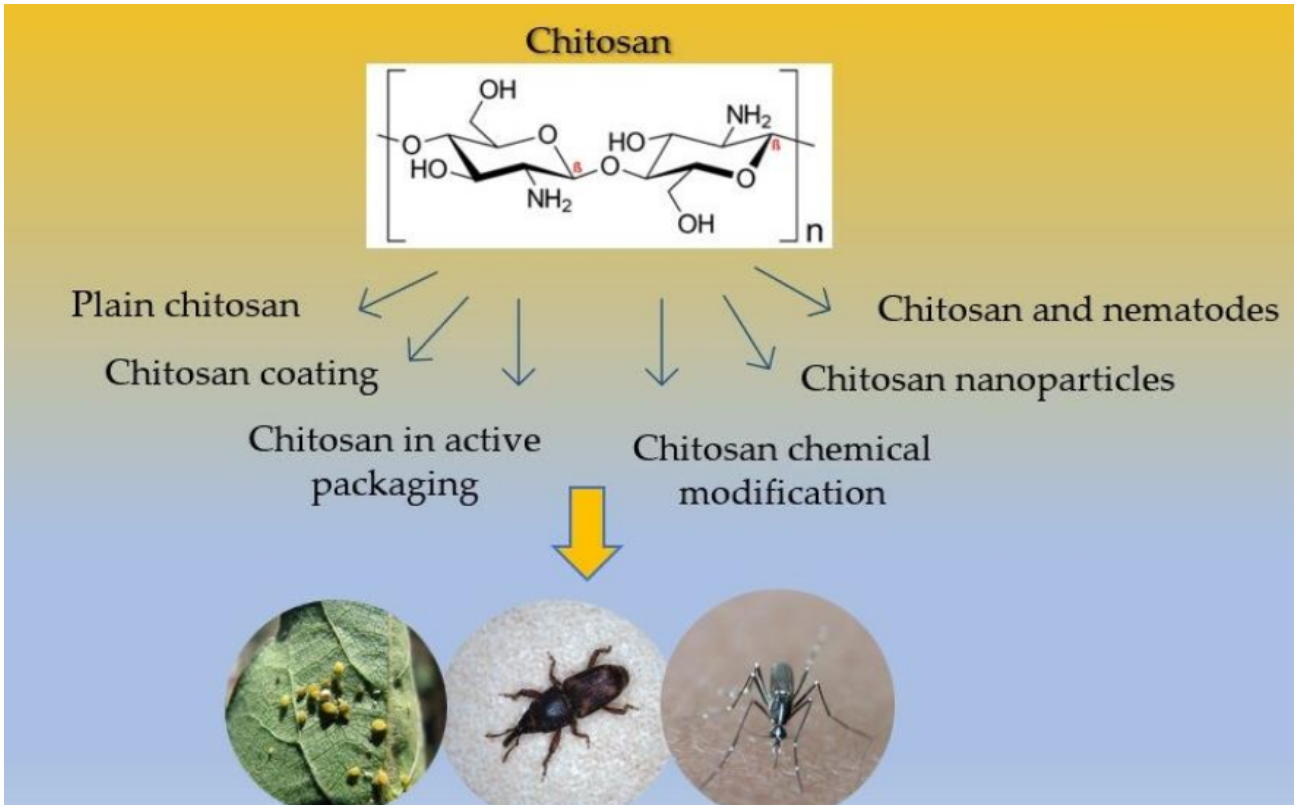

Figure 3. Structural representation of chitosan and its major derivative platforms deployed for sustainable insect pest management. The schematic illustrates the core chemical backbone of deacetylated chitin and its major functionalized forms, including nano-encapsulations, chemical modifications, active coatings, packaging matrices, and bio-nematicidal complexes, used for targeted crop protection and vector control applications (Padamini et al., 2024).

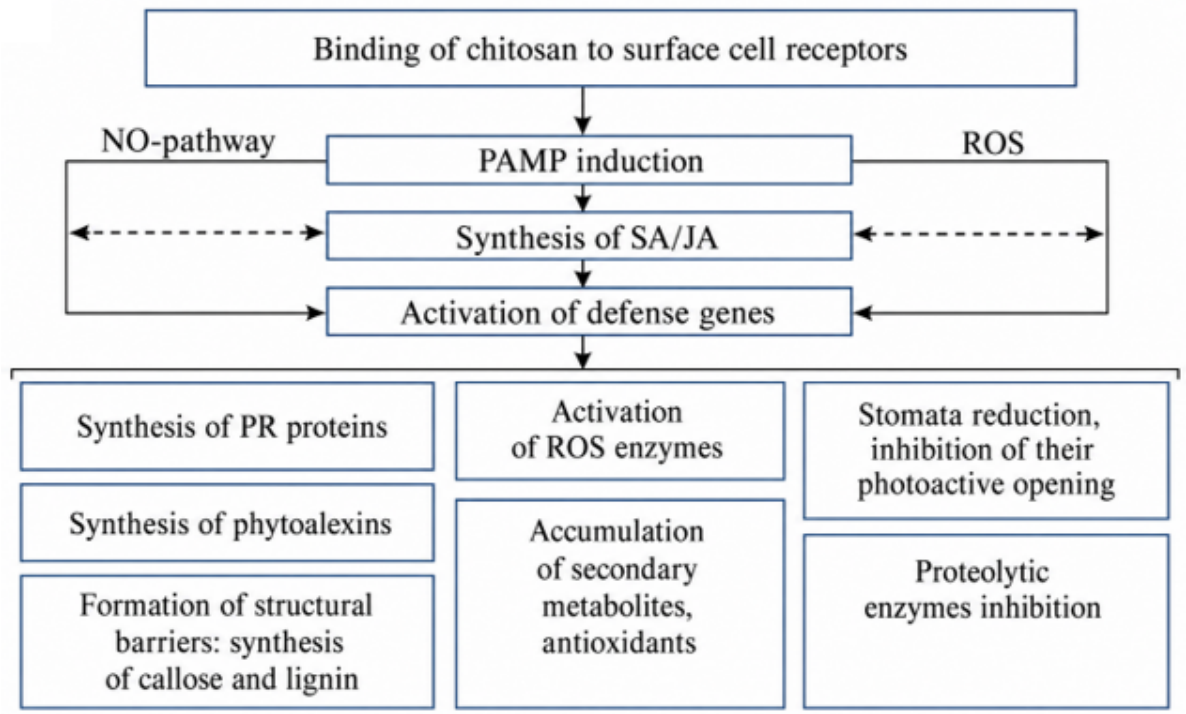

Figure 4. Molecular cascade and signaling pathways involved in chitosan-induced plant immune response and defense gene activation. Exogenous chitosan acts as an elicitor by binding to cell surface receptors, triggering pathogen-associated molecular pattern (PAMP)-triggered immunity. This primary recognition step initiates cross-talk between the nitric oxide (NO) pathway and reactive oxygen species (ROS) accumulation, promoting the biosynthesis of key phytohormones, specifically salicylic acid (SA) and jasmonic acid (JA). Downstream activation of defense-related genes leads to multi-faceted physiological responses, including pathogenesis-related (PR) protein synthesis, phytoalexin production, structural reinforcement via callose and lignin deposition, ROS scavenger/antioxidant accumulation, stomatal closure, and inhibition of pest/pathogen proteolytic enzymes (Shcherban, 2023).

8. Chitosan for Pest Management

Several chitosan derivatives exhibit potent insecticidal and deterrent activities against diverse agricultural pests, while unmodified chitosan enhances the stability and bioavailability of co-formulated botanical extracts and synthetic active ingredients (Sharif et al., 2018) (Figure 3). Recognized as an ecologically benign alternative to conventional synthetic neurotoxic insecticides, chitosan is approved by the European Union as an active, non-toxic basic substance for crop protection under Regulation EC No. 1107/2009. Diverse chitosan formulations are deployed across agricultural and public health sectors to combat insect pests, safeguarding food security while reducing reliance on hazardous chemical inputs (Padamini et al., 2024; Rajkumar et al., 2020).

Chemically characterized as a linear biopolymer of β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units, chitosan serves as an ideal candidate for integrated pest and disease management programs (El Hadrami et al., 2010). Within modern agricultural frameworks, chitosan acts as a biopesticide, a biostimulant for plant growth, a protective seed coating, and a carrier matrix for agrochemicals. Exogenous application of chitosan induces systemic acquired resistance (SAR) and activates defense-related enzymes including peroxidase, polyphenol oxidase, phenylalanine ammonia lyase, and chitinase across cereal, vegetable, and horticultural crops (Kaya et al., 2016). The comprehensive biochemical cascade through which chitosan triggers endogenous plant defense mechanisms is illustrated in Figure 4 (Shcherban, 2023).

Regarding direct pest suppression, chitosan interferes with insect molting, disrupts midgut epithelial membranes, and alters feeding behaviors, while simultaneously inhibiting fungal spore germination, limiting bacterial colonization, and suppressing viral replication (Roohigohar et al., 2020). Chitosan is formulated into diverse delivery systems, including plain chitosan sprays, edible fruit coatings, essential oil composite films, active packaging matrices, chitosan oligosaccharides, and engineered nanoparticle platforms such as chitosan poly acrylic acid nanoparticles, myristic acid chitosan nanoparticles, and chitosan-based systems for RNA interference delivery (Abenaim & Conti, 2023). Recent investigations demonstrate that specialized chitosan preparations exhibit high larvicidal activity against the common house mosquito *Culex pipiens* Linnaeus (Negri et al., 2023). Field and laboratory delivery strategies encompass plain chitosan sprays applied to foliar, timber, or paper matrices, chitosan metal complexes, essential oil-loaded nanoparticles, and combinations with entomopathogenic nematodes (Abenaim & Conti, 2023).

Chemical modifications further enhance the insecticidal potency of chitin derivatives. For instance, N-2-chloro-6-fluorobenzyl-chitosan exhibits high lethality against the oleander aphid *Aphis nerii* Boyer de Fonscolombe and larvae of the Egyptian cotton leafworm *Spodoptera littoralis* (Boisduval) (Rabea et al., 2005). Nano-chitosan formulations composed of chitosan-graft-polyacrylic acid (CS g PAA) function as efficient insecticides against key soybean pests including the cotton aphid *A. gossypii* Glover and the cowpea weevil *Callosobruchus maculatus* (Fabricius) by significantly suppressing female oviposition rates (Sahab et al., 2015). Furthermore, avermectin-grafted N,O-carboxymethyl chitosan (NOCC) provides exceptional insecticidal control against armyworms, carmine spider mites, black bean aphids, and brown planthoppers (Li et al., 2016). Recent ecotoxicological evaluations also reveal that specific chitosan formulations demonstrate marked antimicrobial cytotoxicity against *S. frugiperda* (J.E. Smith) Sf-9 ovarian cell lines, highlighting their potential for targeted cellular disruption in lepidopteran pests (Steglińska et al., 2024).

9. Chitosan as a Plant Protectant Against Insects

9.1. Structural Properties and Structural Modifications for Pest Suppression

Chitosan is a biodegradable, non-toxic biopolymer derived from the partial deacetylation of chitin, and it is widely documented as a sustainable alternative to synthetic chemical pesticides. This biopolymer exerts its crop protective effects by physically disrupting insect exoskeletons, impairing pest reproductive performance, and triggering endogenous plant defense mechanisms. To maximize field efficacy, chitosan is deployed through diverse delivery systems, including plain chitosan, surface coatings, combinations with entomopathogenic nematodes, structural chemical modifications, and engineered chitosan nanoparticles. These advanced nanoparticle formulations offer enhanced systemic mobility within plant tissues and facilitate the prolonged, controlled release of encapsulated botanical active ingredients over time. Chitosan-based protectants are typically applied via foliar sprays, seed treatments, or specialized active packaging matrices (Abenaim & Conti, 2023).

Incorporating plain chitosan at a concentration of 2% into artificial diets induces a severe reduction in the survival period of the housefly *M. domestica* from thirteen days down to four days (Stoffolano et al., 2020). Similar lethal responses are observed in the greenhead horsefly *Tabanus nigrovittatus* Macquart, where survival decreases from sixteen to four and a half days, and in the black blowfly *Phormia regina* (Meigen), where lifespan drops from twenty-four to six days because of severe structural and physiological disruptions within the midgut tract (Stoffolano et al., 2020). Chitosan formulations also interfere with wood boring pests. When applied to paper or timber matrices, chitosan disrupts the feeding behavior of termites and eliminates the essential symbiotic protists residing within the insect digestive tract, and consequently, administering milled paper supplemented with chitosan significantly increases termite mortality compared to untreated controls (Muryeti et al., 2020).

Chitosan is highly effective in preserving structural wood against termite degradation (Liibert et al., 2011). For instance, treating wood with a 2% concentration of chitosan induces a ninety-four percent mortality rate in the eastern subterranean termite *Reticulitermes flavipes* (Kollar) following a twenty-eight-day exposure period (Raji et al., 2018). Similarly, exposures to a lower concentration of 0.5% achieve more than ninety percent mortality in *R. virginicus* (Banks) (Raji et al., 2018). This high mortality correlates with a severe reduction in the populations of key

hindgut protist species responsible for cellulose digestion in *R. virginicus* (Telmadarrehei et al., 2018).

9.2. Post-Harvest Fruit Coatings and Essential Oil Conjugates

Surface coatings utilizing chitosan serve as excellent pre-harvest and post-harvest fruit preservatives. Applying a plain chitosan coating to mango fruits successfully inhibits the egg and larval development of the Mexican fruit flies *Anastrepha ludens* (Loew) and *A. obliqua* (Macquart) (Limon et al., 2021; Salvador-Figueroa et al., 2013). This developmental suppression is driven by a localized increase in the concentration of host phenolic compounds and altered gas exchange dynamics across the fruit pericarp. Furthermore, the altered coloration and structural penetrability of the chitosan layer significantly reduce the visual and olfactory attractiveness of the fruit to foraging pests, thereby preventing successful insect oviposition (Aluja & Mangan, 2008).

Chitosan coatings are frequently enriched with botanical extracts or scaffolding polymers to enhance their repellent properties. A composite film blending a 2% concentration of citronella essential oil with polyethylene glycol and carboxymethylcellulose as scaffolding excipients achieves an eighty-five percent reduction in the oviposition rate of the carambola fruit fly *Bactrocera carambolae* Drew and Hancock when applied to guava fruits (*Psidium guajava* Linnaeus) (Perwita et al., 2020). In arable cropping systems, coating cabbage seeds with chitosan enriched with jasmonic acid induces a fifty-seven percent preimaginal mortality rate in both the diamondback moth *Plutella xylostella* (Linnaeus) and the green peach aphid *Myzus persicae* (Sulzer), effectively halting development before the pests can achieve adult emergence (Haas et al., 2018).

In post-harvest storage and meat preservation, chitosan loaded with essential oils provides a reliable protective barrier against domestic pests. A one percent chitosan coating loaded with a 0.1% concentration of bay laurel (*Laurus nobilis* Linnaeus) or black pepper (*Piper nigrum* Linnaeus) essential oils reduces the oviposition rate of the bluebottle fly *C. vomitoria* (Linnaeus) by 84.9 percent and 93.3 percent, respectively (Farina et al., 2022). For stored cereal protection, incorporating *Eucalyptus* or tea tree essential oils into a chitosan matrix applied to rice grains achieves total mortality of the rice weevil *Sitophilus oryzae* (Linnaeus) at a low concentration of 0.2 µL within 24 to 48 hours (Hossain et al., 2019). When combined with low-dose gamma radiation, this formulation maintains one hundred percent pest mortality even fourteen days after application, ensuring complete disinfestation within food packaging systems.

Chitosan films embedded with *Ferulago campestris* essential oil exhibit a strong, dose-dependent repellent effect under in vitro conditions against the bean weevil *Acanthoscelides obtectus* (Say), achieving a maximum repellency rate of 93.3 percent at a concentration of 57.7 µL per litre of air (Ascrizzi et al., 2021). Notably, this specific essential oil formulation suppresses the germination of competing weed seeds without causing any adverse physiological effects on host bean seed germination or subsequent seedling development (Ascrizzi et al., 2021). Cardboard surfaces coated with a combination of chitosan and lemongrass essential oil provide complete protection against the maize weevil *S. zeamais* (Motschulsky), maintaining one hundred percent toxic efficacy three hundred and sixty hours after the initial treatment (de Fátima Silva et al., 2022).

9.3. Biotic Synergy and Oligosaccharide Infusions

Integrating chitosan with macro-biological control agents and bioactive elicitors represents another highly effective avenue for sustainable pest suppression. Entomopathogenic nematodes are widely recognized biological control agents, with *Steinernema carpocapsae* (Weiser) and its mutualistic bacterial symbiont *Xenorhabdus nematophila* (Poinar and Thomas) representing a versatile combination against the invasive red palm weevil *Rhynchophorus ferrugineus* (Olivier) (Abbas et al., 2001). Laboratory and semi-field experiments demonstrate that combining *S. carpocapsae* suspensions with a chitosan adjuvant actively triggers the endogenous defense mechanisms of Canary Island date palm (*Phoenix canariensis* Chabaud) (Llácer et al., 2009). This molecular synergy stimulates rapid tissue lignification and root development, limiting larval boring damage, while field applications of this chitosan-formulated nematode suspension achieve a 99.7% mortality rate among immature larval stages of *R. ferrugineus* inside the palm stipe (Dembilio et al., 2010).

Foliar applications of chitosan oligosaccharides display potent biopesticidal activity across diverse order lineages. Spraying a chitosan oligosaccharide solution onto infested crop foliage yields a 40% mortality rate against larvae of the cotton bollworm *Helicoverpa armigera* (Hübner) and a 72% mortality rate against the diamondback moth *P. xylostella* within seventy-two hours of treatment (Zhang et al., 2003). This oligosaccharide infusion is exceptionally effective against key hemipteran pests, demonstrating strong aphidicidal control across multiple species, including the bird cherry oat aphid *Rhopalosiphum padi* (Linnaeus), the English grain aphid *Sitobion avenae* (Fabricius), the rose grain aphid *Metopolophium dirhodum* (Walker), the green peach aphid *M. persicae*, the cotton aphid *A. gossypii*, and particularly the mealy plum aphid *Hyalopterus pruni* (Geoffroy), where adult mortality reaches 93% (Zhang et al., 2003).

Chitosan treatments further exhibit marked antifeedant and growth inhibitory properties across major field crops. Utilizing chitosan as a bio-active seed coating for soybean significantly deters feeding by the soybean pod borer and soybean aphid (Zeng et al., 2012). In bioassays against the tobacco cutworm *S. litura* (Fabricius), applying chitosan at a concentration of 3.0 g/L achieves a maximum larval mortality of 62.72% under combined bioassay conditions, outperforming standalone topical application at 52.51% and leaf dip application at 46.14% seven days post-treatment (Uddin et al., 2021). Advanced controlled release delivery systems also enhance biopesticide stability; for instance, a spinosad chitosan-controlled release suspension (SCCS) evaluated at concentrations exceeding 30 mg/L induces greater than 70% mortality in third-instar larvae of *P. xylostella* (Wang et al., 2021).

10. Carrion-centric Insects as Pathogen Vectors: Challenges and Biosecurity Impacts

Carrion-centric insects serve as primary vectors for numerous diseases affecting both human and livestock populations, complicating their role in field-level crop-livestock integrated systems. The prevalence and geographical distribution of these infectious agents are projected to expand across terrestrial and aquatic ecosystems as a consequence of rising global temperatures (Harvell et al., 2002). An increase in the availability of unconsumed carcasses poses a direct biosecurity threat to livestock, wildlife, and public health by facilitating the proliferation of infectious pathogens (Markandya et al., 2008; Pain et al., 2003). Terrestrial environments provide documented examples of significant population surges in vector species driven by these ephemeral resource pulses (Ostfeld & Keesing, 2000).

To effectively mitigate these biosecurity risks and ensure biosecure field integration, management practices must incorporate structured spatial and structural protocols. Regarding perimeter placement, carcass decomposition sites should be located downwind and at a maximum feasible distance from livestock housing, primary water supplies, and human dwellings. Additionally, vermin proof enclosures utilizing fine mesh or wire cages should be deployed to grant access to specialized carrion-centric insects such as burying beetles and blowflies while excluding mammalian scavengers like rodents or feral carnivores that disseminate zoonotic pathogens. Rotational deployment strategies should also be implemented by periodically relocating decomposition stations across field margins to prevent localized pathogen accumulation and persistent soil contamination.

Complementing spatial strategies, rigorous biological and sanitary controls are essential for environmental safety. Health screening requires sourcing experimental or natural necromass exclusively from verified, disease-free livestock stock to eliminate high-consequence veterinary pathogens such as *Bacillus anthracis* (Cohn) or chronic wasting disease prions. Vector monitoring must be conducted systematically to track local dipteran and coleopteran population dynamics, verifying that decomposer communities actively suppress microbial loads without over-amplifying pestiferous or biting fly populations. Furthermore, the application of regulated, ecofriendly soil amendments beneath active decomposition zones can stimulate competitive soil microbiomes that accelerate safe pathogen breakdown.

Climate change represents an acute threat to the stability and functional composition of scavenging communities (Wilson & Wolkovich, 2011). The impact of thermal shifts varies across ecosystems, as decomposition rates approximately double for every 10 °C increase in temperature (Parmenter & MacMahon, 2009; Vass et al., 1992). Projections from climate models suggest that the availability of carrion to terrestrial macrofauna could decline by 20% to 40% over the next century due to accelerated microbial metabolism. Consequently, rising temperatures are likely to disproportionately favor microbial decomposers over carrion feeder insects, potentially reducing terrestrial biodiversity by limiting resources for species dependent on carrion for nutrition (Houston, 1988; Ruxton & Houston, 2004) and reproductive substrates (Rozen et al., 2008). These reductions in carrion availability are particularly severe in polar ecosystems, where they impact the overwinter survival and breeding success of various specialized species (Fuglei et al., 2003).

Furthermore, large-scale pollutants from agricultural and animal industries frequently infiltrate surface water, groundwater tables, and public drinking water supplies. The extensive use and disposal of animals in biomedical research, drug development, safety testing, and education also contribute to the accumulation of chemical contaminants in the environment. These practices, alongside the associated use of diverse chemical supplies, raise significant concerns regarding potential health effects on human populations, necessitating rigorous study within the context of carrion-centric insect ecology (Kolpin et al., 2002; Stackelberg et al., 2004). Given that most vector-borne zoonotic diseases involve wildlife hosts and insect vectors, understanding these dynamics requires multidisciplinary, ecosystem-based studies. Such research is essential to identify the specific hosts, pathogens, and vectors with the greatest potential to impact human and environmental health under evolving climate change scenarios.

11. Balancing Ecological Services and Pathogenic Risks: A One Health Perspective

While the biotechnological and agro-ecological potential of carrion-centric insects is vast, a comprehensive paradigm must reconcile these benefits with the inherent biological risks associated with their role as mechanical and biological pathogen vectors. The One Health framework, an integrated, unifying approach endorsed by international bodies including the Quadripartite alliance of the World Health Organization, Food and Agriculture Organization, World Organisation for Animal Health, and United Nations Environment Programme, recognizes that human, animal, and ecosystem health are inextricably linked and interdependent. Applying this international framework to carrion-centric insects provides a structured methodology to balance the regulating ecosystem services provided by these insects against the biosecurity risks they pose in agricultural and public health domains.

In the context of global warming, the theoretical framing of carrion-centric insects must shift to recognize them as dynamic indicators of ecosystem health rather than static service providers. Climate-driven shifts in ambient temperature and relative humidity significantly accelerate the metabolic rates, developmental velocity, and reproductive cycles of Diptera and Coleoptera, potentially expanding the geographical range and transmission windows of severe zoonotic diseases such as anthrax caused by *B. anthracis* as well as various enteric bacterial pathogens (Rivers & Dahlem, 2014; Vithanage, 1986).

However, this pathogen vector risk is inextricably linked to their fundamental ecological function; the same efficiency in animal carcass biomass removal that prevents large-scale environmental contamination also brings these insects into closer contact with human-mediated landscapes and livestock operations. Therefore, a nature-based sustainable paradigm does not ignore these vector

risks but rather integrates them directly into a One Health management framework. By mass rearing and managing carrion-centric insect populations within biosecure, controlled closed-loop bio-factories for antimicrobial peptide and chitosan extraction (Abdel Rahman et al., 2020; Philibert et al., 2017), researchers and industry can harness their functional potential for green agricultural applications while simultaneously monitoring and mitigating their potential as disease vectors under shifting global climate scenarios (Pain et al., 2003; Rozen et al., 2008).

12. Integration of Global Policy Frameworks

The transition from a traditional vertebrate-centric conservation paradigm to an insect-centric model represents an urgent requirement for fulfilling modern international environmental policy mandates. Specifically, explicit recognition of carrion-feeding insects aligns directly with the Kunming-Montreal Global Biodiversity Framework, adopted in 2022, which prioritizes the restoration, enhancement, and maintenance of nature's contributions to people under Target 11 alongside the protection of ecosystem functional integrity under Goal A. By accelerating organic biomass breakdown, facilitating essential soil nutrient cycling pathways, and preventing the hazardous accumulation of unconsumed organic animal waste, carrion-centric insects provide fundamental regulating ecosystem services. These invertebrate-driven biological processes are foundational to achieving the United Nations Sustainable Development Goals, particularly Goal 15 concerning Life on Land. Formally incorporating the functional roles of carrion-centric insects into national and international conservation agendas provides a measurable, science-based pathway for signatory nations to fulfill their policy commitments toward long-term ecosystem resilience, biodiversity conservation, and sustainable agricultural development.

13. Synthesis, Challenges, and Future Directions

13.1. Current Progress

Considerable milestones have been achieved in integrating carrion-centric insects into mainstream biological and technological research. Closed-loop bio-factories now successfully convert organic municipal and agricultural side streams into uniform insect biomass, mitigating dependency on wild populations. Concurrently, high-throughput transcriptomic sequencing has successfully mapped immune-responsive genes in the common green bottle fly *L. sericata* and the bluebottle fly *C. vicina*, resulting in the discovery of robust peptide structures like lucifensin that maintain structural integrity across diverse chemical matrices. In field-level ecology, the precise quantification of insect-mediated nutrient translocation, especially regarding nitrogen and bioavailable phosphorus fluxes, has transformed the evaluation metrics of natural capital and soil ecosystem services.

13.2. Key Challenges

Despite rapid laboratory breakthroughs, several systemic issues obstruct global commercial and field execution. A primary obstacle involves widespread regulatory and standards gaps, as a unified regulatory framework governing insect-derived agricultural inputs is absent globally. Navigating international safety protocols for insect-harvested antimicrobial peptides and chitosan remains complex due to varying cross-border biosafety classifications. Furthermore, significant vector potential risks exist because open system carrion-centric insect vectors carry critical zoonotic pathogens, which necessitates sophisticated physical isolation barriers during mass rearing cycles and consequently inflates initialization costs. Finally, socio-cultural barriers persist, as public hesitation and consumer resistance toward insect-centric processes in food production and clinical fields continue to impede macro-scale market integration.

13.3. Future Research Horizons

To convert these nature-based options into standard macro-industrial toolkits, future research must prioritize clear strategic directions in paragraph format. Targeted structural bio-engineering requires the optimization of carboxymethylation processes for insect chitin to build targeted, slow-release biopolymeric matrices for smart seed treatments and localized antimicrobial release. In addition, developing synergistic plant protection systems necessitates a comprehensive evaluation of insect antimicrobial peptides combined with native plant growth-promoting fungi or silicon biochar to optimize natural induced resilience against structural field pests. From an epidemiological standpoint, advanced One Health modeling must focus on developing predictive, artificial intelligence-driven biogeographical models to forecast how thermal and precipitation fluctuations will shift insect vector boundaries across vulnerable geographic zones. Lastly, closed-loop agro-industrial optimization will require streamlining mechanical bioconversion pathways to seamlessly integrate animal and crop waste streams directly with automated, self-contained insect multiplication units to ensure safe, stable output quality.

14. Conclusion

The ecological significance of carrion-centric insects extends far beyond their traditional classification as mere scavengers, as they serve as fundamental drivers of nutrient cycling, soil health, and functional ecosystem stability. In the context of modern plant protection systems, these insects play a pivotal role in maintaining agroecosystem resilience. Through the rapid disintegration of organic remains, these insects facilitate the translocation of essential nutrients such as bioavailable nitrogen and phosphorus into the soil matrix and plant rhizosphere, thereby maintaining the homeostatic balance of terrestrial and managed agricultural environments. This review underscores that the functional diversity of carrion-centric insects, particularly within the orders Diptera, Coleoptera, and Hymenoptera, provides a substantial array of ecosystem services that directly bolster plant protection systems. By stimulating beneficial soil microbiomes, enhancing natural crop defenses, and acting as non-bee pollinators for economic crops, these organisms represent an indispensable component of agro-ecological resilience. Despite these multi-faceted contributions, carrion-centric invertebrates remain a frequently overlooked element of natural capital and often suffer from a poor public

reputation that hampers their integration into modern integrated pest management strategies.

At present, global conservation and agricultural policy frameworks are primarily designed around vertebrate taxa, while invertebrates, and carrion-centric species in particular, are systematically overlooked. This oversight is exacerbated by anthropogenic land-use changes and chemical pollution that disrupt the vital biological services these insects provide for crop health and sustainable farming ecosystems. Beyond their natural ecological roles, carrion-centric insects represent a burgeoning frontier in green biotechnology and circular agriculture for sustainable crop protection. The industrial extraction of functional biopolymers such as chitosan and antimicrobial peptides from species like *C. megacephala* offers a sustainable, nature-based alternative to synthetic agrochemicals, providing novel biopesticides, seed coatings, and elicitors of systemic acquired resistance against major crop pathogens and insect pests.

Integrating carrion-centric insect ecology into mainstream plant protection frameworks bridges the gap between natural ecosystem services and active pest management. Despite this immense potential, the stability of carrion-feeding insect communities is increasingly threatened by rising global temperatures and broad-spectrum environmental pollutants, which necessitate urgent multidisciplinary research. Future research must focus on establishing biosecure mass-rearing bio-factories, refining insect biopolymer formulations for targeted crop delivery, and developing predictive One Health models to monitor vector dynamics under changing climate scenarios. Decision-makers across policy, practice, and agricultural business must recognize the necessity of managing this invertebrate capital sustainably. Substantial investment is required to elevate our understanding of carrion-centric insects within megadiverse regions to a level where sustainable development targets can be effectively realized. Promoting the conservation, ecological integration, and managed development of carrion-centric insect populations is not merely a biological necessity, but a strategic requirement for building resilient plant protection systems, sustainable agricultural landscapes, and a biodiverse society.

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