insects

MDPI

Type of the Paper Review)

Optimizing Habitat Management to Boost Beneficial Insect Populations for Effective Rice Pest Control

Gebretsadik Kifle Gebreegziabiher[1,5#], Shuyan Kou[1#], Xianghong Shen[2], Xiang Li[2], Xu Yang[3], Songqiang Li[4], Binbin Huang[4], Cheng Jiang[1], Weihua Liu[1], Zhenhua Zhu[1], Pingrong Yuan[1], Zhigang Wu[1*], Ping Huang[1*]

[1] Institute of Food Crops, Yunnan Academy of Agricultural Sciences, Yunnan Key Laboratory for Rice Genetic Improvement, Kunming 650201, China; kiflegeb2020@gmail.com; sy_kou@yaas.org.cn; zhzhh86@126.com; 2021204023@stu.njau.edu.cn; lwhynu@yaas.org.cn
[2] Yuxi Academy of Agricultural Sciences, Yuxi 653100, China; 759835040@qq.com; 25855734@qq.com
[3] Yunnan Provincial General Station of Agricultural Technology Extension, Kunming 650201, China; ynsnjtgz@163.com
[4] Yuanjiang Hani, Yi and Dai Autonomous County Agricultural Development Service Center, Yuxi 653100, China; Lsq584131@126.com; 18387542539@163.com
[5] Tigray Agricultural Research Institute, Mekelle 492, Tigray, Ethiopia; kiflegeb2020@gmail.com
* Correspondence: wuzhigangswu@yaas.org.cn; tmhping@yaas.org.cn
# These authors contributed equally to this work.

Simple Summary

Rice production is severely affected by insect pests such as planthoppers, stem borers, leafhoppers, and gall midges, which cause major yield losses worldwide. Beneficial insects and other natural enemies, including spiders, ladybird beetles, dragonflies, damselflies, and parasitoid wasps, play a key role in suppressing these pests and reducing reliance on chemical insecticides. This review highlights how habitat management and ecological engineering can strengthen biological control in rice ecosystems. Practices such as maintaining non-crop vegetation, flower strips, banker plants, cover crops, and shelter habitats provide food, alternative hosts, and refuges that enhance the abundance and effectiveness of natural enemies. Increasing biodiversity and landscape heterogeneity generally improves pest suppression, lowers pesticide use, and supports sustainable rice production. Several case studies demonstrate that ecological engineering and conservation biological control can successfully reduce populations of major rice pests, particularly brown planthoppers and stem borers. Overall, the review concludes that habitat management and ecological engineering are essential components of IPM. By conserving and enhancing beneficial insects, these approaches offer environmentally friendly, sustainable solutions to improve rice productivity while reducing reliance on synthetic pesticides. Finally, we outline technical recommendations and future research trajectories to facilitate the integration of habitat manipulation into standard rice integrated pest management frameworks globally.

Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

Copyright: © 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Abstract

Rice is a staple food for more than half of the global population, but its production is threatened by insect pests such as planthoppers, stem borers, leafhoppers, and defoliators. The widespread use of chemical pesticides has raised concerns regarding environmental contamination, pest resistance, and negative effects on beneficial arthropods. This review examines the role of biological control and habitat management in sustainable rice pest management. It highlights the diversity and ecological roles of natural enemies, including

parasitoid wasps, mirid bugs, ladybird beetles, and spiders, which help suppress pest populations in rice ecosystems. Key habitat management approaches, such as conservation biological control, ecological engineering, banker plant systems, flower strips, and the preservation of non-crop habitats, are discussed for their capacity to enhance the abundance and effectiveness of natural enemies. The review also considers integrating these approaches into Integrated Pest Management (IPM) programs to reduce pesticide dependence while maintaining crop productivity. Evidence from rice-growing regions demonstrates the effectiveness of habitat-based strategies in improving pest suppression and strengthening ecosystem resilience. However, challenges related to landscape complexity, farmer adoption, long-term implementation, and the need for a clear roadmap for future landscape-scale entomological research remain. Future research should focus on optimizing habitat management practices and integrating ecological approaches with modern agricultural technologies to support sustainable rice production.

Keywords: Rice; natural enemies; habitat management; ecological engineering; integrated pest management; rice pests

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's three major staple food crops, alongside maize and wheat, and serves as the primary food source for more than half of the global population [44, 84]. Approximately 90% of global rice production occurs in Asia, with China and India serving as the leading producers and consumers of this essential staple crop [129]. China is currently the largest rice-producing country in the world [44]. Despite its global importance, more than 20% of rice production is lost annually to insect pests [57, 132], resulting in significant yield losses and reducing crop quality. The major pest groups include planthoppers [137], generalist leafhoppers, true bugs, and locusts [132], as well as the African rice gall midge, armyworm, and rice stem borers [90]. These pests are naturally regulated by a range of natural enemies, including generalist predators such as spiders and predatory bugs, which have high dispersal capacities, and specialist parasitoids that typically disperse over shorter distances [140].

To advance sustainable agroecology, this review explicitly addresses core entomological questions regarding how specific predatory and parasitic insect taxa respond behaviorally, numerically, and functionally to intentional vegetation modifications. Specifically, we evaluate: (1) How do specialized planthopper egg parasitoids navigate localized landscape heterogeneity to achieve optimal parasitism rates? (2) What nutritional and volatile cues govern the recruitment of beneficial predatory insects to diversified flower strips? and (3) What mechanisms dictate the microclimatic suitability of winter shelters for stabilizing beneficial arthropod populations across cropping seasons? By shifting the analytical focus from generalized biocontrol concepts to specific insect biology and trophic dynamics, this review aims to provide rice entomologists with actionable, ecophysiologically grounded blueprints for conservation biological control. This aligns with recent bibliometric assessments and regional integrated pest management frameworks emphasizing structured, landscape-scale entomological designs [4, 90]. Beneficial insects and other arthropods play crucial roles in providing ecosystem services that help manage rice

Pest populations and reduce dependency on chemical pesticides [12, 88, 119]. Key predators, such as ladybird beetles, spiders, dragonflies, damselflies, rove beetles, and mirid bugs, as well as parasitoids such as *Anagrus* spp. and *Trichogramma* spp., are

fundamental to regulating herbivore populations in rice ecosystems [1, 119]. These natural enemies mitigate pest populations through predation and parasitism, thereby supporting integrated pest management strategies and decreasing reliance on synthetic pesticides [9, 77, 101]. However, the success of biological control largely hinges on the availability of appropriate habitats, food resources, and refuges to sustain natural enemy populations throughout the cropping season [38, 42].

Currently, rice agroecosystems are undergoing significant changes characterized by reduced crop diversity and the loss of semi-natural habitats [37, 132, 140]. Habitat management and ecological engineering have emerged as promising approaches for enhancing biological control in rice-based agroecosystems [48, 97]. These strategies focus on increasing biodiversity through practices such as intercropping, conservation of non-crop vegetation, establishment of flower strips, use of banker plants, and preservation of semi-natural habitats [3, 140]. By offering nectar, pollen, alternative prey, shelter, and overwintering sites, these practices strengthen natural enemy communities and enhance their efficacy in pest suppression [42, 70]. Numerous studies have shown that diversified agricultural landscapes can increase the abundance and effectiveness of predators and parasitoids, resulting in reduced pest pressure, lower insecticide use, and improved crop yields [4, 48, 97, 132].

The success of predatory arthropods is affected by factors such as habitat complexity, availability of alternative prey, and disturbances caused by broad-spectrum insecticides [28, 119]. Spiders, as generalist predators, can capture significant numbers of prey throughout their lifetimes, positioning them as valuable agents for biological pest control [33, 119]. Higher spider diversity contributes to pest suppression as species vary in their hunting strategies and can target a broader range of pests [33, 81]. Understanding the ecological and environmental factors influencing predator populations is essential for optimizing their roles in sustainable agriculture [63, 119].

We argue for the role of beneficial insects and habitat management in sustainable rice pest management. It underscores the diversity and ecological roles of key natural enemies, discusses habitat-manipulation strategies to improve biological control, and assesses ecological-engineering approaches within the context of Integrated Pest Management (IPM). Additionally, it presents case studies highlighting successful habitat-based pest management practices and identifies key challenges and future research directions to foster resilient and environmentally sustainable rice production systems.

2. Rice Pests and Beneficial Insects in Rice Ecosystems

2.1 Common insect pests of rice

Rice production is severely constrained by a wide range of insect pests, including stem borers, hoppers, defoliators, gall midges, and several coleopteran pests [22]. Globally, rice planthoppers (RPHs) represent the most economically destructive pest complex, primarily consisting of the brown planthopper (BPH), *Nilaparvata lugens* (Stål); the white-backed planthopper (WBPH), *Sogatella furcifera* (Horváth); and the small brown planthopper, *Laodelphax striatellus* (Fallén) [137]. These hemipterans extract vascular sap, inducing "hopperburn," and vector critical viral diseases like rice tungro and Rice Yellow Mottle Virus (RYMV) [127]. Lepidopteran stem borers, including *Scirpophaga incertulas* (Walker) and *Chilo suppressalis* (Walker), are similarly devastating; regional meta-analyses demonstrate that every 1% increase in "whiteheads" triggers a 4% decline in grain yield [18, 127]. While conventional production intensification relies heavily on synthetic nitrogen inputs and broad-spectrum chemical sprays, these practices inadvertently improve pest nutritional quality while decimating the natural enemy communities that naturally suppress outbreaks [51]. To optimize the core arguments, an exhaustive taxonomic inventory of

regional secondary pests has been omitted here in favor of focusing on these primary, globally representative threat groups.

2.2 Beneficial Insects in Rice Ecosystems

Natural enemies are major regulators of rice pests and are classified into generalist or specialist functional groups [53]. Generalists, such as predatory spiders, dragonflies (e.g., *Crocothemis servilia* (Drury) and *Orthetrum sabina* (Drury)), damselflies (e.g., *Agriocnemis femina* (Brauer)), and ladybird beetles (e.g., *Micraspis discolor* (Fabricius) and *Harmonia octomaculata* (Fabricius)), consistently suppress varied pest populations across growth stages [16]. For instance, studies have shown that the experimental exclusion of generalist predators can lead to catastrophic pest outbreaks, with target pest populations increasing by as much as 13-fold [53]. Conversely, specialists such as microhymenopteran egg parasitoids (e.g., *Anagrus nilaparvatae* Pang & Wang and *Pseudoligosita yasumatsui* (Subba Rao)) precisely target specific hosts, achieving high natural parasitism rates of up to 70% in undisturbed paddies [106]. Detailed target hosts and mechanisms for these primary taxa are systematically summarized in Table 1.

2.2.1 Factors Threatening Natural Enemies

Beneficial arthropod communities face severe compounding threats from both anthropogenic practices and environmental stressors. Long-term field surveys indicate that dragonfly and damselfly populations are declining at an annual rate of approximately 14%, resulting in an overall 90% decimation over the past two decades due to the widespread adoption of systemic insecticides in aquatic rice systems [87]. Additionally, since rice is an annual monoculture that is harvested in the fall, beneficial insects experience a sudden decline in the availability of alternative prey. This resource scarcity is severely exacerbated by low winter temperatures, which drive high mortality among epigeal spiders and ladybird beetles if adequate vegetated overwintering microhabitats are absent [56].

2.2.2 Synergistic Interactions Among Natural Enemies

Optimizing biological control requires understanding the predator–parasitoid synergistic relationships that occur within the rice canopy and benthos. Generalist foliar predators (such as mirid bugs) and specialized egg parasitoids (such as *Anagrus* spp.) often exploit the same RPH cohorts simultaneously. While intraguild predation can occur, complex habitat architectures minimize negative interference. For example, web-building and ground-hunting spiders selectively target adult and nymphal planthoppers, thereby reducing the overall herbivore pressure and mechanical disturbance on the crop. This suppression allows delicate parasitoid wasps to achieve higher oviposition efficiency on remaining host eggs. Integrating these complementary foraging behaviors stabilizes top-down pest regulation throughout variable phenological phases.

Table 1. Representative natural enemies in rice agroecosystems and their functional roles.

Natural enemy taxon	Functional froup	Primary target pests	Mechanism of action	Reference
Crocothemis servilia (Drury)	Generalist Predator	Planthoppers, leafhoppers, snails	Nymphs and adults prey on active immature and adult insect pests	[4]
Harmonia octomaculata (Fabricius)	Generalist Predator	Aphids, whiteflies, jassids, mites	Foliar search and consumption of soft-bodied insect cohorts	[53,67]
Pardosa pseudoannulata (Bösenberg & Strand)	Generalist Predator	Brown planthopper, leafhoppers	Active ground and lower-canopy hunting in field interiors	[39]

Anagrus nilaparvatae Pang & Wang	Specialist	Parasitoid	Brown planthopper eggs	Endo-parasitoid oviposition into host eggs, causing host mortality	[84]
Trichogramma spp.	Specialist	Parasitoid	Stem borers, leaf folders	Solitary or gregarious egg parasitism of lepidopteran targets	[22,84]

3. Principles of Habitat Management for Conservation Biological Control

Conservation biological control (CBC) is a science-based approach that enhances pest management by conserving and promoting natural enemies within agroecosystems [38]. As a key component of integrated pest management (IPM), CBC offers a more sustainable alternative to excessive chemical pesticide use and helps mitigate the negative effects of agricultural intensification on beneficial organisms [49, 107, 143]. This approach relies on habitat manipulation and modifications in agricultural practices to improve the growth, survival, and effectiveness of natural enemies [38, 70]. Common mechanisms underlying enhanced pest suppression include the provision of alternative food resources such as nectar and pollen, alternative prey or hosts, and shelter [38] (Fig. 3).

Habitat management aimed at conserving natural enemies is fundamental to sustainable pest management and is based on ecological principles that promote stable biological control in agroecosystems [45]. Key strategies include intercropping, no-till farming, preserving non-crop vegetation, cultivating flower strips, increasing connectivity between croplands and unmanaged habitats, and using selective insecticides [10, 24, 38]. In addition, the introduction of plant-derived resources, including nectar, pollen, shelter, and alternative prey, creates favorable conditions that improve the fecundity, longevity, and persistence of natural enemies [42, 143]. By providing access to these essential resources, habitat management enhances the fecundity, longevity, and persistence of natural enemies, thereby reducing reliance on chemical pesticides and promoting sustainable agricultural practices [45, 60, 121].

Numerous studies have shown that increased plant diversity enhances pest management and strengthens ecosystem services by restoring the natural components of agroecosystems [75, 114]. Diversified agricultural landscapes generally support greater abundance and diversity of beneficial organisms, thereby improving the effectiveness of natural enemies [91]. Biodiversity contributes significantly to ecosystem services by restoring the natural components of agroecosystems [5, 75]. Among the various diversification practices, intercropping—defined as the cultivation of two or more crops within the same field during a single growing season—has emerged as an effective non-chemical strategy for enhancing biodiversity and suppressing pests [75]. By supporting a broader range of natural enemies, intercropping reduces pest densities, lowers pesticide costs, and can increase crop yields and economic returns [30, 85]. Furthermore, optimizing intercropping systems requires a better understanding of crop genotypic diversity, natural enemy diversity, and the role of volatile organic compounds (VOCs) in mediating plant–insect interactions [69, 76].

3.1 Biodiversity Enhancement:

Agricultural landscapes are increasingly being simplified through crop homogenization and the loss of semi-natural habitats, threatening arthropod natural enemies and disrupting ecosystem functions [133]. As agricultural practices evolve, changes in landscape structure can influence natural pest regulation, pesticide use, and biodiversity conservation, highlighting the need to enhance habitat diversity within farming systems [4, 132].

Enhancing plant diversity in and around rice fields creates habitats and food for beneficial insects, like predators and parasitoids [3, 132]. This can be achieved through practices such as intercropping, crop rotations, and planting cover crops [4, 94]. Increased crop diversity supports generalist predators, including ladybird beetles, predatory bugs, and spiders, by ensuring a continuous supply of resources [17, 64, 132]. Numerous studies have shown that habitat diversification strengthens biological control in rice ecosystems. For example, increasing landscape diversity enhances parasitoid populations, while incorporating nectar-rich flowering plants promotes natural enemies and reduces crop damage [5, 41, 66] [4, 41, 42]. Similarly, maintaining fallow lands and fragmented habitat patches can reduce insecticide dependence and contribute to sustainable pest management, particularly by supporting ladybird beetle populations [4].

Despite these benefits, biodiversity enhancement does not always lead to improved biological control [65, 116]. Increased crop diversity may adversely affect parasitoids adapted to monocultures and, in some cases, favor pest outbreaks by concentrating host plants [36, 104, 132]. In addition, insect pests and their natural enemies frequently move between crop fields and adjacent semi-natural habitats, influencing their population dynamics [103, 132]. Semi-natural habitats such as flower strips, forests, and grasslands provide resources for natural enemies but may also serve as refuges for pests [71, 112, 134]. Landscape characteristics such as smaller field sizes can facilitate the movement of natural enemies into crop fields [64, 103, 132]. Consequently, effective biological control requires a balanced combination of crop diversity and semi-natural habitats, with landscapes containing approximately 20–50% semi-natural areas generally supporting the highest abundance of natural enemies [64, 132].

3.2 Non-Crop Habitat Management

Diverse non-crop habitats in agricultural areas provide homes for natural enemies, which play a crucial role in pest control within farming systems [115, 117]. These habitats protect natural enemies from insecticides and provide food sources like nectar and pollen, as well as shelter and alternative hosts during winter [42, 115] (Fig.1, 2 & 3). Research indicates that landscape complexity and diversity (i.e., compositional and configurational heterogeneity) significantly influence the abundance and effectiveness of these natural enemies [26, 98, 115]. However, farms with limited non-crop habitat often experience weaker pest control due to biodiversity loss, which disrupts food chains [115].

Distinguishing between the effects of natural enemy communities in simple versus complex landscapes is challenging, as declines in numbers and variety often occur together. Nonetheless, increasing biodiversity has been shown to enhance pest control [15, 114, 115]. For example, enhancing compositional heterogeneity in rice landscapes has been found to boost parasitoid [4, 66]. Additionally, incorporating nearby nectar-rich flowering plants increases natural enemy abundance and reduces crop damage [3, 41] (Fig.2). In agricultural ecosystems that do not utilize chemical pesticides, the naturally occurring populations of beneficial organisms provide significant pest-control advantages for farmers [4].

Evidence of the importance of natural enemies comes from experiments where excluding them with cages led to a significant increase in BPH populations, resulting in a 15.3–37.0% higher grain yield loss [4]. In contrast, uncaged plots and experimental fields maintained low BPH levels, thanks to the presence of natural predators, such as ladybird beetles and spiders, which were frequently observed attempting to enter the cages [4]. Maintaining natural vegetation around rice fields, such as field margins and hedgerows,

can enhance biodiversity and create refuges for beneficial insects [83, 124]. These areas serve as breeding grounds and provide shelter and food resources.

3.3 Ecological Engineering for Pest Management

Ecological engineering is an eco-friendly, effective approach that involves designing and managing agricultural landscapes to enhance natural enemies and suppress pests within an agroecosystem [42, 90]. This approach is grounded in ecological principles that strengthen biological control services while reducing reliance on external inputs, such as insecticides, thereby safeguarding biodiversity [11]. Important practices include establishing cover crops, conserving hedgerows, and maintaining buffer areas that offer shelter and supplementary food resources for beneficial insects [34, 90]. In addition, landscape diversification strategies, including crop rotation and intercropping, help break pest life cycles and lessen their adverse effects on rice production [58, 90, 143]. Non-crop species are added to supply essential resources—nectar, pollen, and alternative prey—and create stable habitats that fill temporal and spatial resource gaps in simplified landscapes [9, 133]. It involves habitat management strategies to conserve and enhance beneficial organisms for effective pest control [11, 78]. These habitat management practices support natural enemies by providing supplementary resources, including pollen, nectar, extrafloral nectar, alternative prey or hosts, and physical refuges [78, 143]. Such outcomes can be achieved by modifying vegetation to promote biological control, regulate herbivorous insects, and minimize the use of plant protection chemicals [48].

3.3.1 Shelter for Natural Enemies

Establishing shelter for natural enemies of rice pests is vital for enhancing biological control, as it supports beneficial insects for overwintering, minimizes insecticide use, and facilitates rapid recolonization [143]. Shelter habitats provide semi-permanent environments with favorable biotic and abiotic conditions for overwintering, aestivation, reproduction, and protection from disturbances associated with agricultural practices such as plowing, spraying, and harvesting [32]. In addition, they enhance the abundance and diversity of natural enemies by providing favorable microclimates, alternative prey or hosts, non-prey food resources, and protection from intraguild predators and pesticide exposure [38, 143]. Natural shelters can be provided by specific plant structures, plant groups, or plant litter that protect natural enemies [38, 70, 113] (Fig. 2c). Among the most prevalent types of shelters are beetle bankers, shelterbelts, hedgerows, flower strips, intercropping, and the selective conservation of arable weeds [38] (Fig. 1&2). Returning rice straw in rice fields and planting green manure crops such as *Astragalus sinicus* after the rice harvest could provide habitats and shelter for native natural predators to overwinter [50] (Fig. 1e). Other ways of providing shelter include incorporating rice straw into the field (Fig. 1d), maintaining Graminaceous plants around rice fields, intercropping with *Zizania latifolia* (Fig. 2b), and neighboring with vegetable crops (Fig. 2a), which increases natural enemies around and within the rice field [143]. These practices can suppress pest populations, minimizing the need for pesticides and promoting sustainable pest management [19, 143].

Providing structured shelter within ecological engineering frameworks is essential for conserving natural enemies, protecting them from chemical disturbances, and facilitating winter survival [143]. Post-harvest fields present severe ecological disruptions; thus, specific agronomic practices must be deployed. Figure 1 details the cyclical management of overwintering shelters. The vibrant crop vegetation before harvest (Fig. 1a) shifts to a bare landscape after harvesting (Fig. 1b), which does not have protective structures. To counteract this, maintaining piles of retained rice straw within the field boundaries

(Fig. 1c) provides an insulating thermal layer that protects native predatory beetles and spiders from freezing temperatures. Similarly, incorporating chopped rice straw directly into the soil surface (Fig. 1d) preserves interstitial spaces that serve as micro-refuges. Post-harvest cultivation of green manure crops, such as *Astragalus sinicus* L. (Fig. 1e), provides alternate vegetative structure and nectar resources, supporting parasitoid survival through winter transitions.

In-season spatial modifications are further illustrated in Fig. 2. Planting diverse vegetable crops directly adjacent to the primary rice plots (Fig. 2a) expands local dietary resources and creates edge-zone shelters that support high initial populations of ladybird beetles. Intercropping rice directly with aquatic vegetables like *Zizania latifolia* (Griseb.) Turcz. Ex Stapf (Fig. 2b) increases canopy structural complexity and provides stable microclimates. Furthermore, establishing multi-strata natural shelterbelts consisting of perennial shrubs and grasses (Fig. 2c) reduces wind stress and provides permanent, pesticide-free breeding zones. Sowing dedicated flower strips along field bunds (Fig. 2d) offers vital non-prey food sources such as nectar, which greatly extend the lifespans of parasitoid wasps.

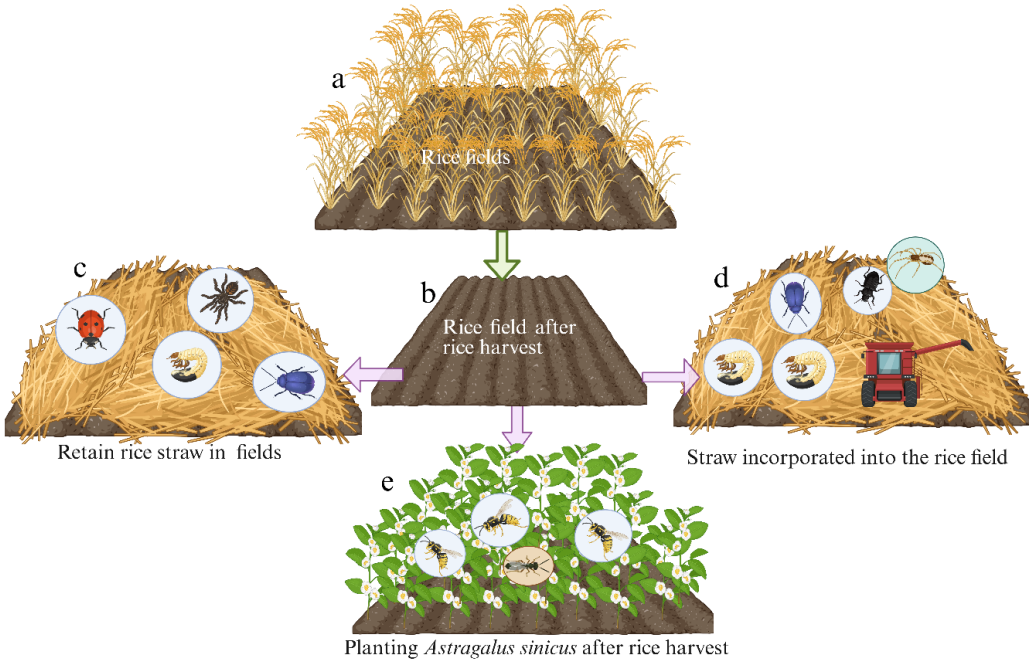


Figure 1. Practices to provide shelter in rice fields: (a) rice fields before harvest; (b) rice fields after harvest; (c) retained rice straw provides habitats and shelter for native predators to overwinter; (d) incorporation of rice straw into the rice field to improve refuge for natural enemies within the field;(e) planting green manure crop (*Astragalus sinicus*) after rice harvest provides resources and shelter for natural enemies during overwintering.

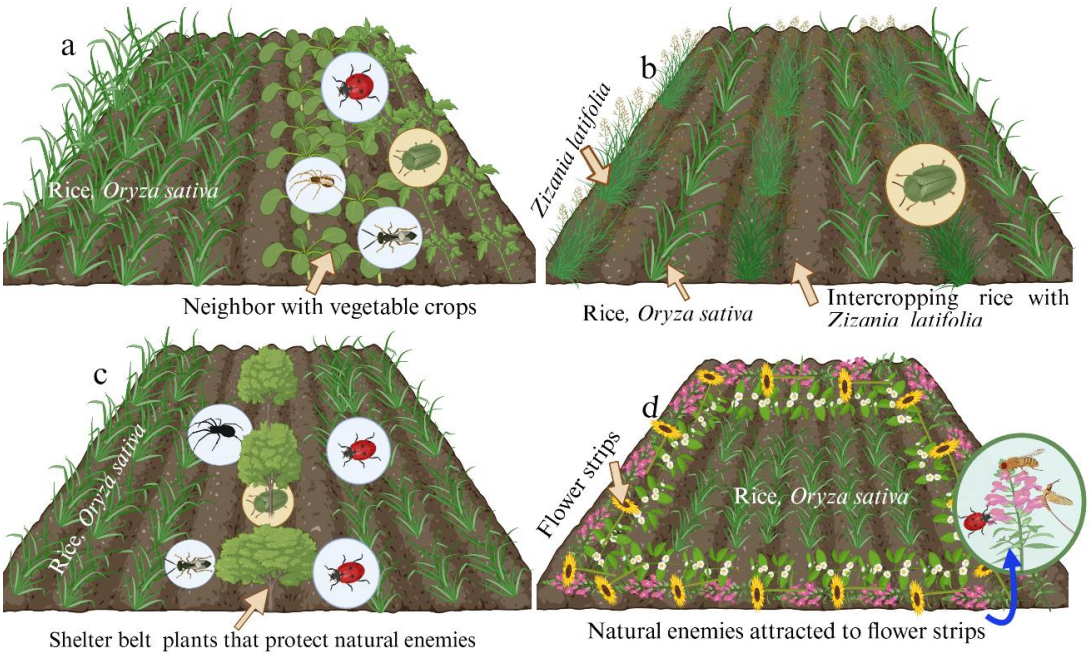


Figure 2. Types of shelters that support natural enemy conservation by providing food resources and alternative hosts: (a) vegetable crops adjacent to rice fields enhance natural enemy populations around and within the fields; (b) intercropping rice with *Zizania latifolia* increases habitat complexity and supplies resources for natural enemies; (c) natural shelter belts provide specific plant resources, diverse vegetation, and litter that protect natural enemies; and (d) flower strips supply essential resources that improve the survival, reproduction, and biocontrol effectiveness of natural enemies.

3.3.2 Alternative Host for Natural Enemies

The functional synchronization between pests and natural enemies is highly mediated by rice phenological stages, which progress through distinct phases: tillering -> booting -> heading -> grain filling -> ripening. During the early tillering phase, primary crop pests are scarce, creating a severe resource bottleneck for specialist parasitoids. Sowing non-crop banker plants solves this issue by supporting harmless alternative herbivores. For instance, the theoretical concept of "functional plants," as defined by Dong et al. [32], emphasizes utilizing species like *Z. latifolia* to maintain stable populations of the non-pest planthopper *Saccharosydne procerus* (Matsumura). This non-pest herbivore serves as a critical alternative host for *Anagrus* egg parasitoids during early tillering, allowing the parasitoids to multiply and suppress BPH populations before they reach damaging levels during the booting and heading stages.

The banker plant system is a conservation biological control (CBC) method that involves nurturing a non-crop plant to support a non-pest herbivore, which attracts natural predators of crop pests [35, 143]. The first successful banker plant system was developed in 1977, involving tomato as the banker plant, a parasitoid *Encarsia formosa Gahan* (Hymenoptera: Aphelinidae), and a whitefly pest *Trialeurodes vaporariorum* Westwood (Homoptera: Aleyrodidae) on tomatoes in greenhouses [109]. Banker plants provide essential food sources, such as shelter, pollen, and nectar, or various hosts or prey, fostering self-sustaining systems that promote the reproduction of beneficial organisms in agricultural environments to control a specific insect pest [20, 32] (Fig. 3).

In rice systems, banker plant systems involve planting sesame (*Sesamum indicum*) as a nectar source to promote the establishment and persistence of the predatory bug *Cyrtorhinus lividipennis* (Heteroptera: Miridae) and of parasitoids *A. nilaparvatae* (Hymenoptera: Mymaridae), *Apanteles ruficrus* (Hymenoptera: Braconidae), *Cotesia chilonis*

(Hymenoptera: Braconidae), and *Trichogramma chilonis* (Hymenoptera: Trichogrammatidae) [141, 142] (Fig. 3). Ideally, the alternative host is a specialist of the banker plant to avoid harming other crops, and the natural enemies must be able to move across the field and target the main pest effectively [143]. This setup prevents the local extinction of pest predators and increases their numbers. Predatory ladybird beetles (Coccinella) and egg parasitoids (*Anagrus* and *Oligosita* wasps) associated with rice pests are commonly found inhabiting wild grasses along rice bunds [4].

These banker plants help maintain populations of beneficial predator species by providing prey during winter and the early rice season when rice pests are rare [138]. Thus, banker plants are planted and maintained near crops to attract insects that can serve as alternative hosts for arthropod natural enemies when pest populations are low or absent [14, 108] (Fig. 3g).

Preserving and utilizing natural predators in rice fields efficiently controls RPHs [143]. Weeds provide shelter for *A. nilaparvatae*, a key egg parasitoid, while delphacidae insects act as alternative hosts [135]. Examples of banker plant systems employed in rice production are the *Z. latifolia* – *Saccharosydne procerus* – *A. nilaparvatae* (ZSA) and *Leersia sayanuka* – *Nilaparvata muiri* – *A. nilaparvatae* and *Typhus chinensis* (LNA and T) [143]. Laboratory research indicated that the BPH could not complete its life cycle on *L. sayanuka*, while *N. muiri* was also unable to develop on rice [143]. Therefore, the cultivation of *L. sayanuka* poses no risk of serving as an alternative host for the rice pest BPH, as field studies show that BPH densities are significantly lower in rice fields integrated with this banker plant than in control fields without it [138, 143]. The ZSA system involves intercropping rice with the aquatic vegetable *Z. latifolia* (Fig. 2b).

The green slender planthopper (GSPH) is the main pest of *Z. latifolia* and provides winter food for the egg parasitoid *A. nilaparvatae*, which it shares with RPHs and leafhoppers [130, 143]. Guo, Zhou [40] found that rice fields with L. sayanuka spaced 5 m apart alongside S. indicum had higher populations of *A. nilaparvatae* during the tillering stage than fields with only *L. sayanuka* or control fields. Their study also indicated significant differences in parasitism rates, which were highest in fields featuring the 5 m combination of *L. sayanuka* and *S. indicum*. Additionally, spider populations were notably higher in this treatment than in others. During the rice tillering stage, fields planted with a combination of *L. sayanuka* and *S. indicum* in strips measuring either 50 cm × 5 m or 50 cm × 1 m exhibited significantly lower RPH populations than the control fields [40]. However, protection levels against natural enemies vary among host plants, emphasizing the need for research on optimal plant-host combinations for conservation biological control [108]. If chosen wisely, plants like Zizania can serve a dual role by offering shelter for various natural enemy taxa while also supporting hosts for more specialized parasitoid species [143]. These findings suggest that carefully selected non-crop plants can strengthen conservation biological control by providing habitat and alternative hosts for natural enemies.

Functional plants are essential for supporting natural enemies by conserving predators and recruiting parasites, stabilizing habitats, and providing alternative foods that enhance their abundance and persistence [23, 133]. Plant functional types are defined as sets of species that exhibit similar responses to environmental conditions and have comparable effects on ecosystem functioning [82, 96]. For instance, woody plants such as *Vitex negundo* and *Prunus persica* maintain predator populations year-round through complementary phenology; *V. negundo* supplies alternative prey during the wheat–rice transition, and its dense structure prevents seasonal declines during fallow periods [122].

Moreover, functional plants play a vital role in supporting parasitoids by providing essential nutrients and chemical cues [133]. Adult parasitoids rely on sugar sources to maximize lifespan and reproduction [9]; for example, *Ocimum basilicum* flowers have been

shown to enhance parasitism rates by offering consistent floral resources [133]. Beyond nutrition, functional plants recruit parasitoids through chemical signals; for instance, *Vigna radiata* emits C6 alkene and alcohol volatiles that boost egg parasitoid populations in corn systems [6]. The combined effects of these functions make functional plants effective and sustainable biological control agents that conserve and enhance natural enemy diversity [42, 123].

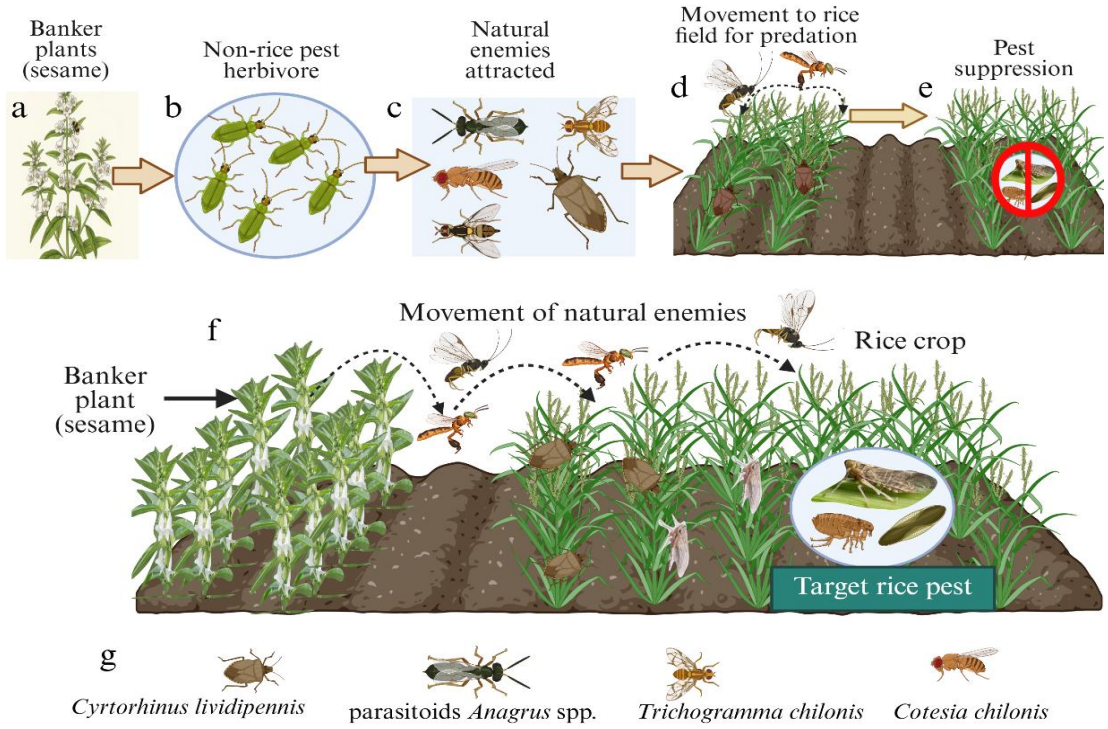


Figure 3. The banker plant system conserves natural enemies for sustainable pest management in rice. (a) Banker plants (sesame) provide essential resources like food (nectar, pollen), shelter, and serve an alternative host/prey for beneficial insects,(b) the banker plant supports non-rice pest herbivores that thrive on them; (c) natural enemies (predators and parasitoids) are attracted and sustained by these herbivores and the plant resources; (d) movement of natural enemies from the banker plants to the rice crop and attack target rice pests; (e) increased natural enemy populations suppress rice pests naturally; (f) natural enemies supported and maintained with the banker plant (sesame) move to rice field suppress target rice pests such as planthoppers, leaf folders, and stem borers; (g) planting banker plants (sesame) as nectar source can enhance the establishment and persistence of key natural enemies.

3.3.3 Floral Resources for Natural Enemies

Flower strips have been incorporated into agricultural practices since the 1990s, particularly in Europe, as part of agri-environmental schemes [13, 59]. These strips provide multiple benefits, such as habitat for beneficial insects, enhancing pollination services, and improving pest control [59, 68] (Fig. 2d). Ideally, flower strips should feature native, perennial species that bloom throughout the growing season to support key beneficial insects and can comprise a mix of annuals and perennials [59, 89]. They have been effectively used in perennial crops and greenhouses, where non-crop areas allow for implementation, such as between tree rows [59, 61, 62, 92]. However, integrating perennial strips into annual field crops poses challenges due to disturbances from plowing, pesticide use, land allocation issues, and large field sizes [59, 61, 62]. While field margins can be utilized, they may provide limited resources for natural enemies. The effectiveness of flower strips in

open landscapes is influenced by their size, quality, and the selection of flowering species [59, 100].

The abundance of natural enemies increases markedly with the species richness of flower strips [79] (Fig. 2d). Greater plant diversity enhances habitat complexity, providing a wider variety of pollen, nectar, and alternative prey, which supports more arthropod natural enemies [59]. While species richness is critical, selecting flower species with functional traits that benefit both specialist and generalist natural enemies is essential [59, 118]. Diverse flower strips (≥2 sown species) increase natural enemy abundance by 70% (±24.7 SE) on average; each additional plant species increases natural enemy abundance by approximately 3.5–4.1% [59]. Jachowicz and Sigsgaard assessed flower strip quality by scoring species based on their effects on predator longevity [46]. They found that higher-quality strips supported greater abundances of natural enemies [59]. Providing suitable host plants can enhance predator longevity and disease resistance, further boosting their populations [46, 111]. In contrast, single-species strips typically have limited traits—such as short flowering periods and low structural diversity—which result in support for fewer natural enemies over shorter durations [54, 59]. However, certain single-species strips, like buckwheat (*Fagopyrum esculentum*) or alyssum (*Lobularia maritima*), can perform well due to their extended flowering periods and high value for predators [46, 59, 80].

Establishing nectar-producing flower strips or patches on rice bunds (levees) can increase the abundance of natural enemies and help reduce pest incidence [3, 41, 52]. Key predators and parasitoids are often abundant in rice fields near vegetation strips [3], potentially reducing the need for insecticide applications and improving rice yields [41, 52]. Parasitoids and foliar predators often gain significant advantages from access to pollen and nectar. For instance, predators like syrphids can traverse greater distances to find these vital resources [59] (Fig. 2d). Conversely, epigeal predators can thrive in complex habitats that offer numerous overwintering sites. However, epigeal predators often benefit from complex habitats that provide abundant overwintering refuges, although their ability to colonize newly established habitats may be limited [74]. Combining resistant rice varieties with vegetation strips can amplify the advantages of both strategies. For instance, vegetation strips paired with resistant rice varieties can further reduce populations of *S. furcifera* and *N. virescens* by enhancing predator and parasitoid diversity near the bunds [3]. Greater arthropod diversity, including herbivores, near vegetation strips is expected to stabilize communities by broadening species interactions, including competition [3].

Floral resources enhance the effectiveness of natural enemies by attracting them, prolonging their lifespan, and boosting their reproductive capacity [73]. Therefore, planting appropriate flowering species in non-crop areas around paddy bunds can enhance the abundance and diversity of key natural enemies, ultimately helping to reduce pest populations [143]. Floral resources lead to higher abundance and reproduction rates of natural enemies, especially in rice systems, resulting in lower pest populations, increased yields, reduced pesticide use, and greater economic returns [73, 126, 143]. Olfactometric tests have shown that flowers from marigold, cowpea, and sesame attract significantly higher numbers of key predators—such as *Micraspis discolor*, *Ophionea nigrofasciata*, and *Cyrtorhinus lividipennis*—as well as parasitoids like *T. chilonis* and *Trichogramma japonicum*, compared to control treatments [78]. Consistent with these findings, field studies have also recorded higher populations of natural enemies, including coccinellids, ground beetles, rove beetles, mirid bugs, damselflies, and spiders, in plots containing flowering plants than in control plots [78]. This attraction is likely driven by volatile compounds emitted from the flowers. Sesame is particularly valued in ecological engineering for rice pest

management due to its dual income benefits and its inclusion in China's nationally recommended sustainable pest control strategies [143].

Sowing flowering strips on field bunds provides vital nectar and pollen that directly improve natural enemy performance. Recent meta-analyses by Jachowicz and Sigsgaard [59] provide crucial quantitative effect sizes for these interventions: highly diverse flower strips comprising two or more sown plant species increase natural enemy abundance by an average of 70% (±24.7% SE) within adjacent crops. Crucially, their modeling reveals a linear benefit where each additional plant species incorporated into the strip increases natural enemy abundance by approximately 3.5–4.1%. This quantitative enhancement occurs because high plant richness ensures overlapping blooming periods and varied floral architectures, which accommodate both generalist ladybird beetles and short-tongued parasitoid wasps.

4. Integrated Pest Management

Integrated Pest Management (IPM) is an environmentally sustainable approach that employs a variety of pest control strategies to keep pest populations below economically damaging levels while reducing risks to human health and the environment [139]. Instead of relying solely on reactive pesticide applications, IPM focuses on a coordinated integration of cultural, biological, physical, and chemical control methods [27, 99] (Fig. 4). This approach prioritizes preventive measures, continuous monitoring, and decision-making based on established economic thresholds, ensuring effective and sustainable pest management.

Key principles of IPM include preventing pest outbreaks through cultural practices such as crop rotation, sanitation, intercropping, and cultivating resistant crop varieties, which help create unfavorable conditions for pest development [43, 102] (Fig. 4a). Regular monitoring through scouting and the establishment of action thresholds allows farmers to evaluate pest populations and determine the right timing for intervention [43, 139] (Fig. 4b). Biological control strategies rely on natural enemies, such as predators, parasitoids, and other beneficial organisms, to regulate pest populations and provide sustainable pest suppression [105] (Fig. 4d). If other methods prove inadequate, chemical control measures, such as biopesticides and selectively targeted pesticides, are applied judiciously to minimize negative environmental impacts [139] (Fig. 4c). By integrating these diverse strategies, IPM offers an effective, economically viable, and ecologically sound approach to pest management in agricultural systems.

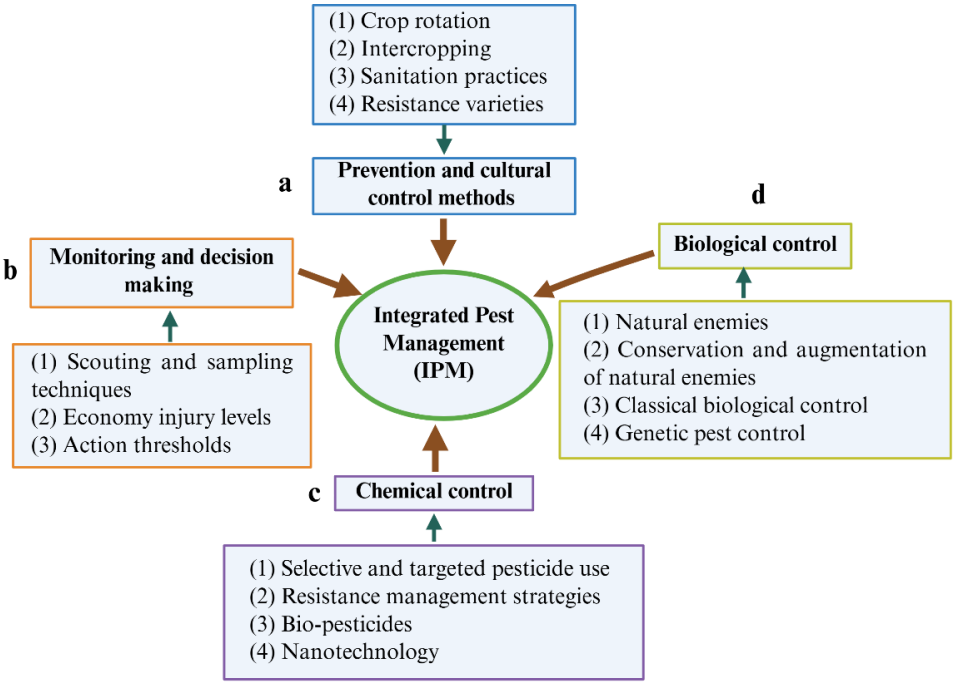


Figure 4. Essential elements of Integrated Pest Management (IPM) involve: (a) prevention and cultural practices such as crop rotation and the use of resistant varieties; (b) monitoring through pest scouting and evaluating economic injury thresholds; (c) chemical controls that include targeted pesticide application and strategies for managing pesticide resistance.

5. Case Studies and Evidence from Biocontrol Systems

Although the evidence base remains geographically uneven, several representative studies illustrate how habitat management can improve pest suppression when interventions are aligned with local ecological conditions and farming systems.

5.1 Landscape Heterogeneity and Natural Pest Suppression in Bangladesh

A two-year field study in Bangladesh used sentinel prey and landscape metrics to quantify biological control services in rice. Predator abundance, especially that of ladybird beetles, was higher in landscapes containing fallow land and vegetated road edges, and a biological control service index increased with landscape diversity while pest density and yield loss declined [4]. This case clearly demonstrates that off-field habitats can influence pest regulation within the crop.

5.2 Ecological Engineering in Zhejiang, China

Large-scale ecological engineering in Zhejiang Province combined flowering plants, reduced insecticide use, and lower nitrogen inputs across operational rice farms. The system supported a greater abundance of *Anagrus* spp., spiders, and other natural enemies and reduced planthopper pressure during critical crop stages, showing that habitat-based biological control can work beyond small research plots when backed by coordinated management and extension [19, 134].

5.3 Landscape Composition and Parasitoid Responses in Stem-Borer Systems

Studies of stem-borer systems in subtropical rice landscapes show that landscape composition influences both pest infestation and parasitoid performance. Specialist parasitoids do not always respond positively to increased non-crop habitat, because host

concentration, dispersal constraints, and alternative-resource use can generate species-specific outcomes [37, 42]. This case illustrates why life-history traits must be considered when generalizing from landscape-diversification studies.

Table 2. Representative case studies illustrating habitat-based biological control in rice systems

Case study	System	Intervention	Main target pest(s)	Main outcome	References
Bangladesh's heterogeneous rice landscapes	Smallholder rice mosaic	Fallow land and vegetated road edges	Brown planthopper	Higher predator abundance and stronger natural pest suppression	[4]
Zhejiang ecological engineering program	Operational rice farms	Flowering plants, reduced insecticide, lower nitrogen	Planthoppers	Higher parasitoid abundance and lower pest pressure	[19,134]
Subtropical stem-borer systems	Landscape-varied rice production	Landscape-level habitat heterogeneity	Stem borers	Species-specific parasitoid responses to landscape composition	[37,42]

6. Challenges and Future Research Agenda

Several challenges continue to hinder the scientific understanding and practical implementation of habitat management in rice cultivation. Firstly, while many studies quantify changes in the abundance of natural enemies, they often fail to establish robust connections between these changes and outcomes such as pest suppression, yield stability, or overall farm profitability. Secondly, much of the existing literature is dominated by short-term experiments, which complicates the assessment of persistence over time, variations in climate, and evolving pest dynamics. Thirdly, the current evidence base is largely focused on Asia, neglecting the unique ecological and socio-economic contexts present in rice systems across Africa and South America [22, 42, 120].

To address these gaps, future research should focus on four key areas. One priority should be to improve testing of mechanisms related to plant traits, volatile cues, natural enemy nutrition, and movement ecology. Another important direction is to design experiments that account for both field-level interventions and landscape contexts. Additionally, there is a need for standardized reporting of effect sizes for natural enemy abundance, parasitism, predation, pesticide reduction, and yield outcomes. Lastly, it is essential to integrate socio-economic analyses that consider factors such as labor requirements, profitability, farmer perceptions, and policy incentives related to ecological engineering [43, 93].

The urgency of addressing these issues is amplified by climate change. Warming temperatures, altered rainfall patterns, and shifting crop and insect phenology are expected to reshape pest pressures and the performance of natural enemies. Therefore, habitat management strategies must be resilient to climate change while maintaining biological functionality [29]. Future ecological engineering efforts should prioritize incorporating locally adapted plant mixtures that provide multiple ecosystem services, including nectar resources, structural refuge, and enhanced support for biodiversity.

7. Conclusion and Prospects

Habitat management holds significant promise for enhancing conservation biological control within rice ecosystems, but its effectiveness hinges on ecological compatibility rather than mere diversification. Key strategies include planting nectar-rich flowering

species along field bunds, creating banker plant refuges, preserving fallow areas, and maintaining diverse vegetation strips adjacent to rice paddies [32, 143, 144]. These enhancements provide essential resources—such as shelter, nectar, and alternative prey—for natural enemies, including predators and parasitoids that target major rice pests like planthoppers and stem borers [8, 141, 143].

Recent evidence indicates that landscape composition and configuration, collectively referred to as landscape heterogeneity, play a critical role in determining the abundance and effectiveness of these natural enemies [4, 7, 31]. Research shows that diverse habitats, like road edges and fallow lands, can support higher populations of beneficial species, such as ladybird beetles and spiders, which are instrumental in controlling brown planthopper populations and reducing yield losses [2, 4]. Moreover, studies suggest a positive correlation between landscape diversity and pest suppression, implying that maintaining heterogeneous, fragmented habitats can reduce the need for preventive insecticide applications [4].

By blending landscape-level diversity with targeted on-field habitat management, ecological engineering offers a scalable and cost-effective approach to enhancing yields, diminishing chemical inputs, conserving biodiversity, and promoting the sustainable intensification of rice production. This strategic habitat manipulation represents a significant shift in global rice protection, encouraging farmers to substitute broad-spectrum chemical treatments with structured non-crop resources. Such a transition not only stabilizes top-down biocontrol services but also ensures high yields and safeguards agricultural biodiversity.

Looking ahead, future research should aim to quantify the specific impacts of various habitat modifications on pest suppression and natural enemy abundance, while also exploring climate-resilient plant species. By developing adaptive strategies to accommodate shifting environmental conditions, we can improve the effectiveness of habitat management in rice agroecosystems and bolster long-term sustainability in global agriculture.

Author Contributions: Conceptualization, G.K.G., S.K., Z.W., and P.H.; drafted the initial manuscript and coordinated revisions, G.K.G., S.K., C.J., Z.W., and P.H.; collected the resources, S.K., X.S., X.L., X.Y., S.L., B.H., C.J., W.L., Z.Z., and P.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Major Projects of Yunnan Science and Technology (202503AM140024,202403AK140011,202403AM140030, 202402AE090002), the XingDian YingCai of Yunnan Province, the Yunnan Science Foundation (202301AT070005), and Yunnan Provincial Key Laboratory of Rice Genetics and Improvement Fund (2026002).

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BPH	Brown planthopper
CBC	Conservation biological control
GSPH	Green slender planthopper
IPM	Integrated pest management
RPHs	Rice planthoppers
RYMV	Rice Yellow Mottle Virus
WBPH	White-backed planthopper
VOCs	Volatile organic compounds

References

1. Abdul Qayyum, M.; Saeed, S.; Naeem-Ullah, U.; Wajid, M.; Siddique, A.; Matloob, A.; Shahid, R.; Ur Rehman Zia, H.U.; Bilal, H.; Ramzan, M. Insect Pest Complex of Wheat Crop. In: Ansari M-u-R, editor. Current Trends in Wheat Research. London: IntechOpen; 2021.
2. Ali, M.; Kabir, M.; Haque, S.; Afrin, S.; Ahmed, N.; Pittendrigh, B.; Qin, X. Surrounding landscape influences the abundance of insect predators in rice fields. *BMC Zoology*. 2020,5,8.
3. Ali, M.P.; Bari, M.N.; Haque, S.S.; Kabir, M.M.M.; Afrin, S.; Nowrin, F.; Islam, M.S.; Landis, D.A. Establishing next-generation pest control services in rice fields: eco-agriculture. *Sci. Rep*. 2019,9,10180.
4. Ali, M.P.; Clemente-Orta, G.; Kabir, M.M.M.; Haque, S.S.; Biswas, M.; Landis, D.A. Landscape structure influences natural pest suppression in a rice agroecosystem. *Sci. Rep*. 2023,13,15726.
5. Altieri, M.A. Ethnoscience and biodiversity: key elements in the design of sustainable pest management systems for small farmers in developing countries. *Agric. Ecosyst. Environ*. 1993,46,257-72.
6. Amanu, E.; Tana, T.; Amsalu, B.; Dechassa, N. Effects of maize and mung bean intercropping on performance of the component crops and system productivity. *EJCS*. 2021,9,109-38.
7. Baba, Y.G.; Kusumoto, Y.; Tanaka, K. Effects of agricultural practices and fine-scale landscape factors on spiders and a pest insect in Japanese rice paddy ecosystems. *BioControl*. 2018,63,265-75.
8. Babendreier, D.; Tang, R.; Horgan, F.G. Prospects for integrating augmentative and conservation biological control of leaffolders and stemborers in rice. *Agronomy*. 2022,12,2958.
9. Baker, B.P.; Green, T.A.; Loker, A.J. Biological control and integrated pest management in organic and conventional systems. *BioControl*. 2020,140,104095.
10. Beers, E.H.; Mills, N.J.; Shearer, P.W.; Horton, D.R.; Milickzy, E.R.; Amarasekare, K.G.; Gontijo, L.M. Nontarget effects of orchard pesticides on natural enemies: lessons from the field and laboratory. *BioControl*. 2016,102,44-52.
11. Bommarco, R. Ecological redesign of crop ecosystems for reliable crop protection. A review. Agron. Sustain. Dev. 2024,44,1-51.
12. Brzozowski, L.; Mazourek, M. A sustainable agricultural future relies on the transition to organic agroecological pest management. *Sustainability*. 2018,10,2023.
13. Bullock, J.M.; McCracken, M.E.; Bowes, M.J.; Chapman, R.E.; Graves, A.R.; Hinsley, S.A.; Hutchins, M.G.; Nowakowski, M.; Nicholls, D.J.E.; Oakley, S.; Old, G.H.; Ostle, N.J.; Redhead, J.W.; Woodcock, B.A.; Bedwell, T.; Mayes, S.; Robinson, V.S.; Pywell, R.F. Does agri-environmental management enhance biodiversity and multiple ecosystem services? A farm-scale experiment. *Agric. Ecosyst. Environ*. 2021,320,107582.
14. Busuulwa, A.; Revynthi, A.M.; Liburd, O.E.; Lahiri, S. Banker plant efficacy to boost natural predators for management of field populations of *Scirtothrips dorsalis* Hood (Thysanoptera Thripidae) in strawberries. *Insects*. 2024,15,776.
15. Cardinale, B.J.; Harvey, C.T.; Gross, K.; Ives, A.R. Biodiversity and biocontrol: emergent impacts of a multi-enemy assemblage on pest suppression and crop yield in an agroecosystem. *Ecol. Lett*. 2003,6,857-865.
16. Chaitanya, M.; Pavan, J.; Vireesha, P.; Nekkanti, A. Natural enemies as guardians of crop ecosystem with special emphasis on rice and cotton. *J. Exp. Agric. Int*. 2024,46,600-612.
17. Chaplin-Kramer, R.; O'Rourke, M.E.; Blitzer, E.J.; Kremen, C. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett*. 2011,14,922-32.
18. Chen, B.; Chen, Y.; Chen, H.; Liang, Z.; Chen, J.; Wu, R.; Zhang, T.; Zhou, G.; Yang, X. Identification, characterization and prevalence in southern China of a new *Recilia iflavirus* in the leafhopper *Recilia dorsalis* (Hemiptera: Cicadellidae). *Virus Res*. 2023,323,199005.
19. Chen, G.; Zhu, P.; Zheng, X.; Yao, X.; Zhang, F.; Sheng, X.; Xu, H.; Lu, Z. The practice of ecological engineering on the control of rice insect pests in Jinhua. *China Plant Protection*. 2016;36(1):31-6.
20. Chen, X.; Jaworski, C.C.; Dai, H.; Liang, Y.; Guo, X.; Wang, S.; Zang, L.-S.; Desneux, N. Combining banker plants to achieve long-term pest control in multi-pest and multi-natural enemy cropping systems. *J. Pest Sci*. 2022,95,685-697.
21. Claridge, M.; Morgan, J.; Steenkiste, A.; Iman, M.; Damayanti, D. Seasonal patterns of egg parasitism and natural biological control of rice brown planthopper in Indonesia. Agricultural and forest Entomology. 1999;1(4):297-304.
22. Conde, S.; Catarino, S.; Ferreira, S.; Temudo, M.P.; Monteiro, F. Rice pests and diseases around the world: Literature-based assessment with emphasis on Africa and Asia. *Agriculture*. 2025;15(7):667.
23. Cortez-Madrigal; Hipolito; Gutierrez-Cárdenas; Giovanni, O. Enhancing biological control: conservation of alternative hosts of natural enemies. *EJBPC*. 2023,33,25.
24. Dainese, M.; Montecchiari, S.; Sitzia, T.; Sigura, M.; Marini, L. High cover of hedgerows in the landscape supports multiple ecosystem services in Mediterranean cereal fields. *J. Appl. Ecol*. 2017,54,380-388.
25. Daravath, V.; Chander, S. Feeding efficiency of wolf spider, *Pardosa pseudoannulata* (Boesenberg and Strand) against brown planthopper, *Nilaparvata lugens* (Stal). *J. Entomol. Zool. Stud*. 2017,5,5-8.
26. Dassou, A.G.; Tixier, P. Response of pest control by generalist predators to local-scale plant diversity: a meta-analysis. *Ecol. Evol*. 2016,6,1143-53.
27. Deguine, J.-P.; Aubertot, J.-N.; Flor, R.J.; Lescourret, F.; Wyckhuys, K.A.; Ratnadass, A. Integrated pest management: good intentions, hard realities. A review. *Agron. Sustain. Dev*. 2021,41,38.

28. Del-Val, E.; Ramírez, E.; Astier, M. Comparison of arthropod communities between high and low input maize farms in Mexico. *CABI Agric. Biosci*. 2021,2,40.
29. Deutsch, C.A.; Tewksbury, J.J.; Tigchelaar, M.; Battisti, D.S.; Merrill, S.C.; Huey, R.B.; Naylor, R.L. Increase in crop losses to insect pests in a warming climate. *Science*. 2018,361,916-919.
30. Diyaolu, C.O.; Folarin, I.O. The role of biodiversity in agricultural resilience: protecting ecosystem services for sustainable food production. *IJRPR*. 2024,5,1560-73.
31. Dominik, C.; Seppelt, R.; Horgan, F.G.; Settele, J.; Václavík, T. Landscape composition, configuration, and trophic interactions shape arthropod communities in rice agroecosystems. *J. Appl. Ecol*. 2018,55,2461-72.
32. Dong, Z.; Yang, Q.; Wyckhuys, K.A.; Ouyang, F.; Gurr, G.M.; Han, P.; González-Chang, M.; van der Werf, W.; Men, X.; Ge, F. Use of functional plants to enhance pest biological control in farming landscapes: progress and prospects. *Entomol. Gen*. 2026,46,21-37.
33. Elhamalawy, O.; Bakr, A.; Eissa, F. Impact of pesticides on non-target invertebrates in agricultural ecosystems. *Pestic. Biochem. Physiol*. 2024,202,105974.
34. Evans, A. Ecological engineering for pest management. *Agric. Sci*. 2005,143,326-.
35. Frank, S.D. Biological control of arthropod pests using banker plant systems: past progress and future directions. *BioControl*. 2010,52,8-16.
36. Gagic, V.; Hänke, S.; Thies, C.; Scherber, C.; Tomanović, Z.; Tscharntke, T. Agricultural intensification and cereal aphid–parasitoid–hyperparasitoid food webs: network complexity, temporal variability and parasitism rates. *Oecologia*. 2012,170,1099-109.
37. Gong, S.; Zhu, Y.; Fu, D.; Bianchi, F.J.; van Der Werf, W.; Hodgson, J.A.; Xiao, H.; Zou, Y. Land consolidation impacts the abundance and richness of natural enemies but not pests in smallholder rice systems. *J. Appl. Ecol*. 2024,61,1587-1598.
38. Gontijo, L.M. Engineering natural enemy shelters to enhance conservation biological control in field crops. *Biocontrol*. 2019,130,155-63.
39. Guo, J.; Fu, X.; Zhao, S.; Shen, X.; Wyckhuys, K.A.; Wu, K. Long-term shifts in abundance of (migratory) crop-feeding and beneficial insect species in northeastern Asia. *J Pest Sci.* 2020,93,583-94.
40. Guo, X.; Zhou, Q.Y.; Ru, M.M.; Cao, B.; Huang, X.; Zheng, X.S.; Zhu, P.Y. Effects of a bank plant on the control of rice planthoppers: A field study. *Ann. Agric. & Crop Sci.*2024,4,1163.
41. Gurr, G.M.; Lu, Z.; Zheng, X.; Xu, H.; Zhu, P.; Chen, G.; Yao, X.; Cheng, J.; Zhu, Z.; Catindig, J.L. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat. Plants*. 2016,2,16014.
42. Gurr, G.M.; Wratten, S.D.; Landis, D.A.; You, M. Habitat management to suppress pest populations: progress and prospects. *Annu. Rev. Entomol*. 2017,62,91-109.
43. Han, P.; Rodriguez-Saona, C.; Zalucki, M.P.; Liu, S.-s.; Desneux, N. A theoretical framework to improve the adoption of green Integrated Pest Management tactics. *Commun. Biol*. 2024,7,337.
44. Hang, S.; Wang, Q.; Wang, Y.; Xiang, H. Evolution of rice cultivar performance across China: A multi-dimensional study on yield and agronomic characteristics over three decades. *Agronomy*. 2024,14,2780.
45. Hassan, K.; Pervin, M.; Mondal, F.; Mala, M. Habitat management: A key option to enhance natural enemies of crop pest. *Univers. J. Plant Sci*. 2016,4,50-57.
46. He, X.; Kiær, L.P.; Jensen, P.M.; Sigsgaard, L. The effect of floral resources on predator longevity and fecundity: A systematic review and meta-analysis. *BioControl*. 2021,153,104476.
47. He, X.; Qiao, Y.; Sigsgaard, L.; Wu, X. The spider diversity and plant hopper control potential in the long-term organic paddy fields in a sub-tropical area, China. *Agric. Ecosyst. Environ*. 2020,295,106921.
48. Heong, K.-L.; Lu, Z.-X.; Chien, H.-V.; Escalada, M.; Settele, J.; Zhu, Z.-R.; Cheng, J.-A. Ecological engineering for rice insect pest management: The need to communicate widely, improve farmers' ecological literacy, and policy reforms to sustain adoption. *Agronomy*. 2021,11,2208.
49. Holland, J.M.; Bianchi, F.J.; Entling, M.H.; Moonen, A.C.; Smith, B.M.; Jeanneret, P. Structure, function and management of semi-natural habitats for conservation biological control: a review of European studies. *Pest Manag. Sci*. 2016,72,1638-1651.
50. Hong-Xing, X.; Ya-jun, Y.; Yan-Hui, L.; Xu-song, Z.; Jun-ce, T.; Feng-xiang, L.; Qiang, F.; Zhong-xian, L. Sustainable management of rice insect pests by non-chemical-insecticide technologies in China. *Rice Sci*. 2017,24,61-72.
51. Horgan, F.G.; Crisol, E. Hybrid rice and insect herbivores in Asia. *Ent. exp. & appl*. 2013,148,1-19.
52. Horgan, F.G.; Crisol Martínez, E.; Stuart, A.M.; Bernal, C.C.; de Cima Martín, E.; Almazan, M.L.P.; Ramal, A.F. Effects of vegetation strips, fertilizer levels and varietal resistance on the integrated management of arthropod biodiversity in a tropical rice ecosystem. *Insects*. 2019,10,328.
53. Hsu, G.C.; Ou, J.A.; Ni, M.H.; Lin, Z.H.; Ho, C.K. Generalist predators function as pest specialists: Examining diet composition of spiders and ladybeetles across rice crop stages. *Appl. Ecol*. 2025;62(8):1889-901.
54. Hu, W.; Ni, K.; Zhu, Y.; Liu, S.; Shao, X.; Yu, Z.; Wang, L.; Zhang, R.; Duan, M.; Xu, W. Plant-driven effects of wildflower strips on natural enemy biodiversity and pest suppression in an agricultural landscape in Hangzhou, China. *Agronomy*. 2025,15,1286.
55. Huang, J.; Zhou, K.; Zhang, W.; Deng, X.; van Der Werf, W.; Lu, Y.; Wu, K.; Rosegrant, M.W. Uncovering the economic value of natural enemies and true costs of chemical insecticides to cotton farmers in China. *Environ. Res. Lett*. 2018,13,064027.
56. Huang, S.; Wang, L.; Liu, L.; Fu, Q.; Zhu, D. Nonchemical pest control in China rice: a review. *Agron. Sustain. Dev*. 2014,34,275-291.

57. Huang ShiWen, H.S.; Wang Ling, W.L.; Liu LianMeng, L.L.; Fu Qian, F.Q.; Zhu DeFeng, Z.D. Nonchemical pest control in Chinese rice: a review. *Agron. Sustain. Dev*. 2014,34,275-91.
58. Huss, C.; Holmes, K.; Blubaugh, C. Benefits and risks of intercropping for crop resilience and pest management. *J. Econ. Entomol*. 2022,115,1350-1362.
59. Jachowicz, N.; Sigsgaard, L. Highly diverse flower strips promote natural enemies more in annual field crops: A review and meta-analysis. *Agric. Ecosyst. Environ*. 2025,381,109412.
60. Jacob, H.S.; Evans, E.W. Influence of carbohydrate foods and mating on longevity of the parasitoid *Bathyplectes curculionis* (Hymenoptera: Ichneumonidae). *Environ. Entomol*. 2000,29,1088-95.
61. Jacobsen, S.K.; Sigsgaard, L.; Johansen, A.B.; Thorup-Kristensen, K.; Jensen, P.M. The impact of reduced tillage and distance to field margin on predator functional diversity. *J. Insect Conserv*. 2022,26,491-501.
62. Jacobsen, S.K.; Sørensen, H.; Sigsgaard, L. Perennial flower strips in apple orchards promote natural enemies in their proximity. *Crop Prot*. 2022,156,105962.
63. Jarpla, M.; Kumari, P.; Pawar, P.; Reddy, N.; Bhargavi, C.; Samreen, M.; Aniket, E. A review on the role of beneficial insects in sustainable crop production systems. *J. Exp. Agric. Int.* 2024,46,687-699.
64. Jaworski, C.C.; Thomine, E.; Rusch, A.; Lavoir, A.-V.; Wang, S.; Desneux, N. Crop diversification to promote arthropod pest management: A review. *Agric. Commun*. 2023,1,100004.
65. Jaworski, C.C.; Thomine, E.; Rusch, A.; Lavoir, A.-V.; Xiu, C.; Ning, D.; Lu, Y.; Wang, S.; Desneux, N. At which spatial scale does crop diversity enhance natural enemy populations and pest control? An experiment in a mosaic cropping system. *Agronomy*. 2022;12(8):1973.
66. Jeanneret, P.; Aviron, S.; Alignier, A.; Lavigne, C.; Helfenstein, J.; Herzog, F.; Kay, S.; Petit, S. Agroecology landscapes. *Landsc. Ecol*. 2021,36,2235-2257.
67. Joseph, A.R.; Premila, K. A study on the richness of spider fauna in rice ecosystem. *J. Entomol. Zool. Stud*. 2016,4,425-430.
68. Kowalska, J.; Antkowiak, M.; Sienkiewicz, P. Flower strips and their ecological multifunctionality in agricultural fields. *Agriculture*. 2022;12(9):1470.
69. Lamzira, R.; El Fakhouri, K.; Boulamtat, R.; Kemal, S.A.; Oubayoucef, A.; Ramdani, C.; Meftah Kadmiri, I.; El Bouhssini, M. Multifunctional roles of intercropping in the management of insect pests affecting pulse crops: a comprehensive bibliometric analysis. *Front. Sustain. Food Syst*. 2025,9,1599254.
70. Landis, D.A. Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic Appl. Ecol*. 2017,18,1-12.
71. Laterza, I.; Dioli, P.; Tamburini, G. Semi-natural habitats support populations of stink bug pests in agricultural landscapes. *Agric. Ecosyst. Environ*. 2023,342,108223.
72. Liu, S.-S.; Zhang, G.-M.; Zhang, F. Factors influencing parasitism of *Trichogramma dendrolimi* on eggs of the Asian corn borer, *Ostrinia furnacalis*. *BioControl*. 1998,43,273-287.
73. Lu, Z.X.; Zhu, P.Y.; Gurr, G.M.; Zheng, X.S.; Read, D.M.; Heong, K.L.; Yang, Y.J.; Xu, H.X. Mechanisms for flowering plants to benefit arthropod natural enemies of insect pests: prospects for enhanced use in agriculture. *Insect Sci*. 2014,21,1-12.
74. Maas, B.; Brandl, M.; Hussain, R.I.; Frank, T.; Zulka, K.P.; Rabl, D.; Walcher, R.; Moser, D. Functional traits driving pollinator and predator responses to newly established grassland strips in agricultural landscapes. *J. Appl. Ecol*. 2021,58,1728-1737.
75. Mala, M.; Mollah, M.M.I.; Baishnab, M. Importance of intercropping for biodiversity conservation. *J. Sci. Technol. Environ. Inform*. 2020,10,709-716.
76. Markovic, D.; Seimandi-Corda, G.; Harizanova, V.; Stoeva, A.; Himanen, S.; Saussure, S.; Radonjic, A.; Đurić, G.; Lalićević, I.; Kheam, S.; Rensing, M.; Gallinger, J.; Cook, S.M.; Ninkovic, V. Volatile-mediated plant interactions: an innovative approach to cultivar mixture selection for enhanced pest resilience. *Front. Plant Sci*. 2025,16,1550678.
77. McCravy, K.W. A review of sampling and monitoring methods for beneficial arthropods in agroecosystems. *Insects*. 2018,9,170.
78. Meera, K.; Sreeja, P.; Karthikeyan, K.; Smitha, R. Floral resources as ecological tools to enhance natural enemies for pest management in the rice ecosystem. *Plant Sci. Today*. 2026,13,1-8.
79. Mei, Z.; de Groot, G.A.; Kleijn, D.; Dimmers, W.; van Gils, S.; Lammertsma, D.; van Kats, R.; Scheper, J. Flower availability drives effects of wildflower strips on ground-dwelling natural enemies and crop yield. *Agric. Ecosyst. Environ*. 2021,319,107570.
80. Mercer, N.H.; Bessin, R.T.; Obrycki, J.J. Impact of buckwheat and methyl salicylate lures on natural enemy abundance for early season management of *Melanaphis sacchari* (Hemiptera: Aphididae) in sweet sorghum. *Crop Protection*. 2020,137,105279.
81. Michalko, R.; Pekár, S.; Entling, M.H. An updated perspective on spiders as generalist predators in biological control. *Oecologia*. 2019,189,21-36.
82. Miedema Brown, L.; Anand, M. Plant functional traits as measures of ecosystem service provision. *Ecosphere*. 2022,13, 3930.
83. Mkenda, P.A.; Ndakidemi, P.A.; Mbega, E.; Stevenson, P.C.; Arnold, S.E.J.; Gurr, G.M.; Belmain, S.R. Multiple ecosystem services from field margin vegetation for ecological sustainability in agriculture: scientific evidence and knowledge gaps. *PeerJ*. 2019,7, 8091.
84. Mohidem, N.A.; Hashim, N.; Shamsudin, R.; Che Man, H. Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture*. 2022,12,741.
85. Moreira, B.; Gonçalves, A.; Pinto, L.; Prieto, M.A.; Carocho, M.; Caleja, C.; Barros, L. Intercropping systems: An opportunity for environmental conservation within nut production. *Agriculture*. 2024,14,1149.

86. Musa, N.N.; Hatta, S.K.M.; Yaakop, S. Diversity and assemblage patterns of ladybirds (Coccinellidae) in different crop management practices in *Peninsular Malaysia*. *Arthropod Plant Interact*. 2024;18(4):723-40.
87. Nakanishi, K.; Yokomizo, H.; Hayashi, T.I. Were the sharp declines of dragonfly populations in the 1990s in Japan caused by fipronil and imidacloprid? An analysis of Hill's causality for the case of *Sympetrum frequens*. *ESPR*. 2018,25,35352-3564.
88. Nchu, F. Sustainable biological control of pests: The way forward. *Appl. Sci*. 2024,14,2669.
89. Nichols, R.N.; Holland, J.M.; Goulson, D. A novel farmland wildflower seed mix attracts a greater abundance and richness of pollinating insects than standard mixes. *Insect Conserv. Divers*. 2023;16(2):190-204.
90. Pegalepo, E.; Bocco, R.; Onaga, G.; Nwilene, F.; Tamò, M.; Togola, A.; Katiyar, S.K. Sustainable insect pest management options for rice production in Sub-Saharan Africa. *Insects*. 2025,16,1175.
91. Perrin, R.; Phillips, M. Some effects of mixed cropping on the population dynamics of insect pests. *Ent. exp. & appl*. 1978,24,585-593.
92. Pfiffner, L.; Cahenzli, F.; Steinemann, B.; Jamar, L.; Bjørn, M.C.; Porcel, M.; Tasin, M.; Telfser, J.; Kelderer, M.; Lisek, J.; Sigsgaard, L. Design, implementation and management of perennial flower strips to promote functional agrobiodiversity in organic apple orchards: A pan-European study. *Agric. Ecosyst. Environ*. 2019,278,61-71.
93. Pretty, J.; Pervez Bharucha, Z. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*. 2015,6,152-182.
94. Qiu, T.; Shi, Y.; Peñuelas, J.; Liu, J.; Cui, Q.; Sardans, J.; Zhou, F.; Xia, L.; Yan, W.; Zhao, S.; Peng, S.; Jian, J.; He, Q.; Zhang, W.; Huang, M.; Tan, W.; Fang, L. Optimizing cover crop practices as a sustainable solution for global agroecosystem services. *Nat. Commun*. 2024,15,10617.
95. Quandahor, P.; Kim, L.; Kim, M.; Lee, K.; Kusi, F.; Jeong, I.-h. Effects of agricultural pesticides on the decline in insect species and individual numbers. *Environments*. 2024,11,182.
96. Ravnjak, B.; Bavcon, J.; Čarni, A. Plant functional traits of plant species colonizing forest gaps. *Diversity*. 2023,15,973.
97. Rosida, N.; Ibrahim, E.; Senoaji, W.; Sidik, E.A.; Mugiasih, A.; Khaerana; Hutasoit, R.T.; Firmansyah; Praptana, R.H.; Sudewi, S. Harnessing flowering bund plants through ecological engineering to improve biological control of tungro virus vectors in Indonesian rice fields agro-ecosystem. *Int. J. Food Sci*. 2025,2025,2476370.
98. Rossetti, M.R.; Tscharntke, T.; Aguilar, R.; Batáry, P. Responses of insect herbivores and herbivory to habitat fragmentation: a hierarchical meta-analysis. *Ecol. Lett*. 2017,20,264-272.
99. Rossi, V.; Caffi, T.; Salotti, I.; Fedele, G. Sharing decision-making tools for pest management may foster implementation of Integrated Pest Management. *Food Security*. 2023,9,41130-4147.
100. Rowe, L.; Gibson, D.; Landis, D.A.; Isaacs, R. Wild bees and natural enemies prefer similar flower species and respond to similar plant traits. *BAAE*. 2021,56,259-269.
101. Rusch, A.; Bommarco, R.; Ekbom, B. Conservation biological control in agricultural landscapes. *Advances in botanical research*. 81: Elsevier; 2017. p. 333-60.
102. Scheff, D.S.; Phillips, T.W. Integrated pest management. *Storage of Cereal Grains and Their Products*: Elsevier; 2022. p. 661-75.
103. Schneider, G.; Krauss, J.; Boetzl, F.A.; Fritze, M.-A.; Steffan-Dewenter, I. Spillover from adjacent crop and forest habitats shapes carabid beetle assemblages in fragmented semi-natural grasslands. *Oecologia*. 2016,182,1141-1150.
104. Schneider, G.; Krauss, J.; Riedinger, V.; Holzschuh, A.; Steffan-Dewenter, I. Biological pest control and yields depend on spatial and temporal crop cover dynamics. *J. Appl. Ecol*. 2015,52,1283-1292.
105. Shao, X.; Zhang, Q.; Zhang, B.; Xie, Z.; Xu, K. Biological control of insect pests in agroecosystems: Current challenges, innovative strategies, and future directions. *Agriculture*. 2026,16,597.
106. Shi, L.; Liu, D.; Qiu, L.; Jiang, Z.; Zhan, Z. Evaluation of the parasitism capacity of a thelytoky egg parasitoid on a serious rice pest, *Nilaparvata lugens* (Stål). *Animals*. 2022,13,12.
107. Shields, M.W.; Johnson, A.C.; Pandey, S.; Cullen, R.; González- Chang, M.; Wratten, S.D.; Gurr, G.M. History, current situation, and challenges for conservation biological control. *BioControl*. 2019,131,25-35.
108. Skellern, M.P.; Clark, S.J.; Ferguson, A.W.; Watts, N.P.; Cook, S.M. Banker plant bonuses? The benefits and risks of including brassicas in field margins to promote conservation biocontrol of specialist pests in oilseed rape. *Insects*. 2023,14,349.
109. Stacey, D. Banker plant production of *Encarsia formosa* Gahan and its use in the control of glasshouse whitefly on tomatoes. *Plant Pathology*. 1977,26,63-66.
110. Stiling, P.; Cornelissen, T. What makes a successful biocontrol agent? A meta-analysis of biological control agent performance. *BioControl*. 2005,34,236-246.
111. Sun, Y.X.; Chen, M.J.; Hao, Y.N.; Wang, S.S.; Zhang, C.L. Canola bee pollen is an effective artificial diet additive for improving larval development of predatory coccinellids: a lesson from *Harmonia axyridis*. *Pest Manag. Sci*. 2024,80,2920-2928.
112. Thomine, E.; Rusch, A.; Desneux, N. Predators do not benefit from crop diversity but respond to configurational heterogeneity in wheat and cotton fields. *Landsc. Eco*. 2023,38,439-47.
113. Tixier, P.; Duyck, P.-F.; Côte, F.-X.; Caron-Lormier, G.; Malézieux, E. Food web-based simulation for agroecology. *Agron Sustain. Dev*. 2013,33,663-670.
114. Tooker, J.F.; Frank, S.D. Genotypically diverse cultivar mixtures for insect pest management and increased crop yields. *J. Appl. Ecol*. 2012,49,974-985.

115. Tooker, J.F.; O'Neal, M.E.; Rodriguez-Saona, C. Balancing disturbance and conservation in agroecosystems to improve biological control. *Annu. Rev. Entomol*. 2020,65,81-100.
116. Tscharntke, T.; Karp, D.S.; Chaplin-Kramer, R.; Batáry, P.; DeClerck, F.; Gratton, C.; Hunt, L.; Ives, A.; Jonsson, M.; Larsen, A. When natural habitat fails to enhance biological pest control–Five hypotheses. *Biol. Conserv*. 2016,204,449-458.
117. Tscharntke, T.; Tylianakis, J.M.; Rand, T.A.; Didham, R.K.; Fahrig, L.; Batáry, P.; Bengtsson, J.; Clough, Y.; Crist, T.O.; Dormann, C.F. Landscape moderation of biodiversity patterns and processes- eight hypotheses. *Biol. Rev*. 2012,87,661-685.
118. Tschumi, M.; Albrecht, M.; Entling, M.H.; Jacot, K. High effectiveness of tailored flower strips in reducing pests and crop plant damage. *Proc Biol Sci.* 2015,282,1814.
119. Vălean, A.M.; Suciu, L.; Tărău, A.; Șopterean, L.; Russu, F.; Șimon, A.; Chețan, F.; Tritean, N. Impact of shelterbelts on the diversity and dynamics of natural enemies in wheat agroecosystems. *Agronomy*. 2025,15,2153.
120. Van Klink, R.; August, T.; Bas, Y.; Bodesheim, P.; Bonn, A.; Fossøy, F.; Høye, T.T.; Jongejans, E.; Menz, M.H.; Miraldo, A. Emerging technologies revolutionise insect ecology and monitoring. *Trends ecol. evol*. 2022,37,872-885.
121. Wackers, F.L. Gustatory response by the Hymenopteran parasitoid Cotesia glomerata to a range of nectar and honeydew sugars. *J. Chem. Ecol*. 1999,25,2863-2877.
122. Wan, N.F.; Ji, X.Y.; Deng, J.Y.; Kiær, L.P.; Cai, Y.M.; Jiang, J.X. Plant diversification promotes biocontrol services in peach orchards by shaping the ecological niches of insect herbivores and their natural enemies. *Ecol. Indic*. 2019,99,387-392.
123. Wan, N.F.; Zheng, X.R.; Fu, L.W.; Kiær, L.P.; Zhang, Z.; Chaplin-Kramer, R.; Dainese, M.; Tan, J.; Qiu, S.Y.; Hu, Y.Q.; Tian, W.D.; Nie, M.; Ju, R.T.; Deng, J.Y.; Jiang, J.X.; Cai, Y.M.; Li, B. Global synthesis of effects of plant species diversity on trophic groups and interactions. *Nat Plants*. 2020,6,503-510.
124. Wang, C.; Bian, Z.; Wang, S.; Liu, X.; Zhang, Y. The effect of artificial field margins on epigeic arthropod functional groups within adjacent arable land of Northeast China. *Land*. 2022,11,1910.
125. Wang, G.H.; Wang, X.Q.; Qiao, F.; Zhu, Z.R.; Cheng, J.A. Development and preliminary application of a triplex real-time polymerase chain reaction assay for evaluating predation on three planthoppers in a rice ecosystem. *Mol. Ecol. Resour*. 2013,13,811-819.
126. Wang, J.-h.; Ren, B.-b.; Shao, J.-l.; Li, W.; Che, S.-c. Impact of plant community structure and its diversity on richness and abundance of arthropod aphidophagous natural enemy community. *Urban Forestry & Urban Greening*. 2023,81,127850.
127. Wilson, B.E.; Villegas, J.; Stout, M.; Landry, K. Relative yield loss from stem borers (Lepidoptera: Crambidae) and rice water weevil (Coleoptera: Curculionidae) in rice. *J. Econ. Entomol*. 2021,114,1159-1165.
128. Wong, S.-S.; Ooi, P.A.-C.; Wong, W.-L. Antennal and ovipositor sensilla of *Pseudoligosita yasumatsui* (Hymenoptera: Trichogrammatidae). *J. Asia. Pac. Entomol*. 2019,22,296-307.
129. Xu, J. From grain to diversity: The role of rice in shaping the dietary and cultural fabric of eastern China. *Int. J. Gastron. Food Sc*i. 2025,41,101215.
130. Xusong; Zheng; Xiaoping, Y. Dispersal patterns of natural enemies of rice planthoppers between zizania and rice fields. *Acta Agriculturae Zhejiangensis.* 1999,11,339-343.
131. Yang, H.; Peng, Y.; Tian, J.; Wang, J.; Wei, B.; Xie, C.; Wang, Z. Rice field spiders in China: A review of the literature. *J. Econ. Entomol*. 2018,111,53-64.
132. Yang, Q.; Jaworski, C.C.; Wen, Z.; Desneux, N.; Ouyang, F.; Dai, X.; Wang, L.; Jia, J.; Zheng, H. Crop heterogeneity may not enhance biological control of rice pests in landscapes rich in semi-natural habitats. *Agric. Ecosyst. Environ*. 2025,379,109354.
133. Yang, Q.; Li, Q.; Liu, X.; Yang, Y.; Ruan, Y.; Zhu, P.; Lu, Z.; Cao, C.; Lu, Y. The potential of landscape plants *Photinia fraseri* and *Pittosporum tobira* as refuge for natural enemies of pest insects in rice–wheat rotation systems. *Insects*. 2026,17,428.
134. Yang, Q.; Li, Z.; Ouyang, F.; Men, X.; Zhang, K.; Liu, M.; Guo, W.; Zhu, C.; Zhao, W.; Reddy, G.V. Flower strips promote natural enemies, provide efficient aphid biocontrol, and reduce insecticide requirement in cotton crops. *Entomol. Gen.* 2022,43,421-432.
135. Yu, X.; Hu, C.; Heong, K.L. Parasitization and preference characteristics of egg parasitoids from various habitats of homopterans Kun Chong Xue Bao. *Acta Entomol. Sin*.1998,41,41-7.
136. Zang, L.-S.; Wang, S.; Zhang, F.; Desneux, N. Biological control with Trichogramma in China: history, present status, and perspectives. *Annu. Rev. Entomol*. 2021,66,463-484.
137. Zhang, H.; He, B.; Xing, J.; Lu, M. Spatial and temporal patterns of rice planthopper populations in South and Southwest China. Comput. Electron. Agric. 2022,194,106750.
138. Zheng, X.; Lu, Y.; Zhu, P.; Zhang, F.; Tian, J.; Xu, H.; Chen, G.; Nansen, C.; Lu, Z. Use of banker plant system for sustainable management of the most important insect pest in rice fields in China. *Sci. Rep*. 2017,7,5581.
139. Zhou, W.; Arcot, Y.; Medina, R.F.; Bernal, J.; Cisneros-Zevallos, L.; Akbulut, M.E.S. Integrated pest management: An update on the sustainability approach to crop protection. *ACS Omega*. 2024,9,41130-4147.
140. Zhu, P.; Liang, R.; Qin, Y.; Xu, H.; Zou, Y.; Johnson, A.C.; Zhang, F.; Gurr, G.M.; Lu, Z. Extrafloral and floral nectar promote biocontrol services provided by parasitoid wasps to rice crops. *Entomol. Gen*. 2023,43,971-979.
141. Zhu, P.; Lu, Z.; Heong, K.; Chen, G.; Zheng, X.; Xu, H.; Yang, Y.; Nicol, H.I.; Gurr, G.M. Selection of nectar plants for use in ecological engineering to promote biological control of rice pests by the predatory bug, *Cyrtorhinus lividipennis*, (Heteroptera: Miridae). *PLoS One*. 2014,9, e108669.
142. Zhu, P.; Wang, G.; Zheng, X.; Tian, J.; Lu, Z.; Heong, K.L.; Xu, H.; Chen, G.; Yang, Y.; Gurr, G.M. Selective enhancement of parasitoids of rice Lepidoptera pests by sesame (*Sesamum indicum)* flowers. *BioControl*. 2015,60,157-167.

143. Zhu, P.; Zheng, X.; Johnson, A.C.; Chen, G.; Xu, H.; Zhang, F.; Yao, X.; Heong, K.; Lu, Z.; Gurr, G.M. Ecological engineering for rice pest suppression in China. A review. *Agron Sustain. Dev*. 2022,42,69.
144. Zhu, P.; Zheng, X.; Yao, X.; Xu, H.; Zhang, F.; Chen, G.; Lu, Z. Ecological engineering technology for enhancement of biological control capacity of egg parasitoids against rice planthoppers in paddy fields. *China Plant Protection*. 2015,35,27-32.