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Biological Control of Wheat Pests: A Meta-Analysis

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Abstract Biological control provides a sustainable and environmentally friendly alternative to chemical methods for managing agricultural pests. Wheat, as a major global crop, faces significant threats from pest infestations and requires effective management strategies. This study conducted a meta-analysis to evaluate the effectiveness, sustainability, and influencing factors of biological control strategies for wheat pests. The role of key control factors such as parasitic wasps, predatory insects, entomopathogenic fungi, and bacteria in suppressing pest populations was analyzed, emphasizing the advantages of biological control over chemical methods, especially in terms of long-term sustainability and ecological benefits. It was found that climate conditions, crop management practices, and interactions with local biodiversity have a significant impact on the success of biological control work. Case studies from specific wheat planting areas demonstrated the practical application and challenges of implementing biological strategies, introduced new biological control agents, integrated with precision agriculture, and the potential for policy interventions to improve the effectiveness of biological control in wheat pest management. The sentence is:. This study aims to emphasize the importance of promoting biological control as the cornerstone of sustainable agriculture.
Keywords Biological control; Wheat pests; Parasitoids; Predatory insects; *Entomopathogenic fungi*

1 Introduction

Biological control, a cornerstone of integrated pest management (IPM), leverages natural predators, parasitoids, and pathogens to manage pest populations in agricultural systems. This approach aims to reduce reliance on synthetic pesticides, which are often associated with environmental degradation and health risks (Ratto et al., 2022a; Ratto et al., 2022b). Various strategies, such as intercropping, habitat manipulation, and the introduction of biocontrol agents like *Trichogramma* spp., have been explored to enhance the effectiveness of biological control (Lopes et al., 2016). These methods not only help in maintaining pest populations below economic thresholds but also promote biodiversity and ecosystem health (Wyckhuys et al., 2013; Redlich et al., 2018).

Wheat (*Triticum aestivum* L.) is a critical staple crop, providing a significant portion of the global population's caloric intake. It is extensively cultivated in temperate regions and is vital for food security worldwide (Bajwa et al., 2020). However, wheat production faces substantial challenges from various pests, including insects, pathogens, and nematodes, which can cause significant yield losses and economic damage (Qi et al., 2019). The traditional reliance on chemical pesticides for pest control in wheat farming has led to issues such as pesticide resistance, environmental pollution, and adverse health effects (Veres et al., 2020; Ivezić et al., 2022). Consequently, there is an urgent need for sustainable pest management practices that can mitigate these challenges while ensuring stable wheat production (del-Val et al., 2023).

This study evaluated the impact of various biological control strategies on the abundance of wheat field pests, crop damage, and natural enemy populations, including examining the effects of different biological control methods (such as intercropping, habitat manipulation, and the use of specific biological control agents) on pest management outcomes, and exploring the potential of integrating these biological control practices into a broader IPM framework to improve their effectiveness and sustainability in wheat production systems. This study aims to conduct a comprehensive meta-analysis on the effectiveness of biological control interventions in managing wheat pests, providing valuable insights for policymakers, researchers, and farmers to adopt more sustainable and effective pest management strategies in wheat cultivation.

2 Key Biological Control Agents for Wheat Pests

2.1 Role of parasitoids in pest population suppression

Parasitoids play a crucial role in the biological control of wheat pests by parasitizing and ultimately killing their hosts. Notable examples include *Trichogramma pretiosum* and *Encarsia formosa*, which have been extensively studied for their effectiveness against various pests (Koller et al., 2023). These parasitoids are often used in combination with other biocontrol agents to enhance their efficacy. For instance, combining parasitoids with entomopathogenic microorganisms like *Beauveria bassiana* and *Metarhizium anisopliae* has shown promising results in laboratory settings, with most combinations being compatible and effective in pest suppression. However, the timing and dosage of biopesticides are critical to minimize adverse effects on parasitoid development.

2.2 Predatory insects and their impact on wheat pest control

Predatory insects are another vital component of biological control strategies for wheat pests. Predators such as the gall midge *Aphidoletes aphidimyza* have been successfully used to suppress aphid populations in various crops, including wheat (De Azevedo et al., 2017). These predators can significantly reduce pest populations when used alone or in combination with other biocontrol agents. For example, the combination of *A. aphidimyza* with the entomopathogenic fungus *Metarhizium brunneum* has been shown to be more effective in controlling aphid populations than either agent used alone, although the suppression was less than additive. This highlights the potential of integrating multiple biocontrol agents to achieve more effective pest management.

2.3 Entomopathogenic fungi and bacteria in managing pest outbreaks

Entomopathogenic fungi and bacteria are increasingly being recognized for their potential in managing pest outbreaks in wheat. Species such as *Beauveria bassiana* and *Metarhizium brunneum* have been widely studied and used as biocontrol agents due to their ability to infect and kill a broad range of insect pests (Keyser et al., 2016; González-Guzmán et al., 2022). These fungi can be applied directly to the soil or plant surfaces, where they infect pests through contact. Studies have shown that these fungi can effectively reduce pest populations in both laboratory and greenhouse conditions (Dakhel et al., 2019; Wakil et al., 2021). Additionally, entomopathogenic fungi can also act as endophytes, colonizing plant tissues and providing additional benefits such as plant growth promotion and enhanced resistance to pathogens (Bamisile et al., 2021). This dual role makes them valuable components of integrated pest management (IPM) strategies.

3 Efficacy of Biological Control Strategies

3.1 Success stories from field trials

Field trials have demonstrated the effectiveness of various biological control strategies in managing wheat pests. For instance, intercropping systems have shown significant reductions in pest abundance compared to monoculture systems, although the increase in natural enemies was not always significant (Lopes et al., 2016). Another successful approach involved the use of allelopathic bacteria for weed control, which reduced grain yield losses due to weed invasion by up to 76.3% in pot trials and 60.7% in field trials (Abbas et al., 2020). Additionally, the use of wildflower strips within wheat fields significantly reduced aphid populations and supported natural enemies like hoverflies (Hatt et al., 2017). These examples highlight the potential of biological control methods to reduce pest populations and enhance crop yields effectively.

3.2 Comparative analysis of biological versus chemical control methods

Comparative studies have shown that biological control methods can be as effective as chemical treatments in managing wheat pests. For example, a study comparing biological and chemical treatments for controlling fungal diseases in winter wheat found that a combined treatment of bioagents and reduced doses of fungicides was the most effective, achieving high grain yields and protein content (Rebouh et al., 2022). Similarly, a meta-analysis of biocontrol interventions in sub-Saharan Africa revealed that biological control reduced pest abundance and crop damage while maintaining natural enemy populations, performing comparably to synthetic pesticides in terms of pest control and yield (Figure 1) (Ratto et al., 2020a). These findings suggest that biological control methods can offer a sustainable alternative to chemical pesticides, with the added benefit of preserving natural enemy populations.

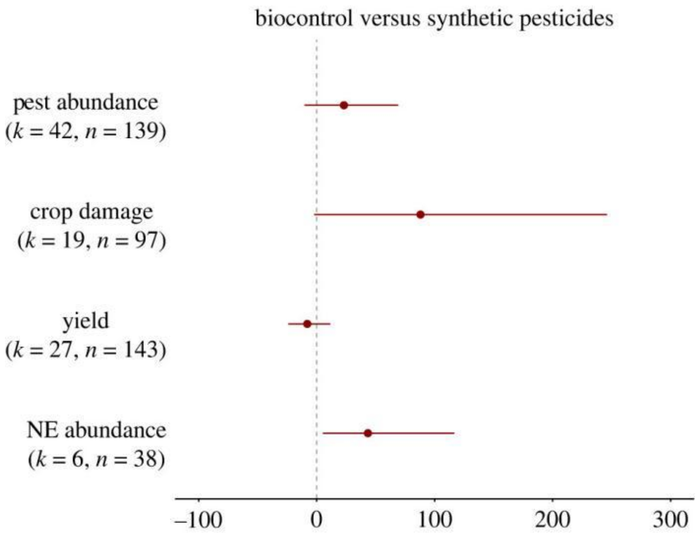

Figure 1 Changes in pest abundance, crop damage, yield and natural enemy (NE) abundance when biocontrol interventions are implemented compared to crops treated with synthetic pesticides. The values are expressed in percentage with 95% bias-corrected confidence intervals. Results that cross zero indicate no significant difference between control and treatment groups. *k*=number of articles, *n*=number of effect sizes (Adopted from Ratto et al., 2020a)

3.3 Long-term sustainability of biological control practices

The long-term sustainability of biological control practices is supported by their ability to integrate with other pest management strategies and reduce reliance on chemical inputs. For instance, combining crop resistance with biological control has been shown to reduce pest population growth more effectively than either strategy alone, even in the presence of antagonistic interactions (Rand et al., 2020). Additionally, the use of slow-release plant infochemicals in a push-pull strategy has demonstrated potential for sustainable aphid control by attracting natural enemies and repelling pests (Zhou et al., 2016). Furthermore, the economic viability of biological control methods has been highlighted, with Pareto-efficient strategies offering high efficacy at small costs (Lundstrom et al., 2016). These examples underscore the potential for biological control practices to provide long-term, sustainable solutions for pest management in wheat production.

4 Factors Influencing the Success of Biological Control

4.1 Climatic conditions and their effects on control agent performance

Climatic conditions significantly impact the performance of biological control agents in wheat pest management. Climate change, characterized by increased temperatures, altered precipitation patterns, and elevated CO_2 levels, can enhance the growth, virulence, and range expansion of wheat pests, complicating pest management strategies. For instance, rapid climatic changes can create new geographic windows for pest outbreaks, making it challenging to maintain effective biological control (Bajwa et al., 2020). Additionally, climate warming has been linked to earlier and more frequent pest attacks, necessitating adjustments in integrated pest management (IPM) strategies to account for these shifts (Malschi et al., 2015). Therefore, understanding and adapting to these climatic influences is crucial for the success of biological control in wheat production.

4.2 Crop management practices and their role in supporting biological control

Crop management practices play a pivotal role in supporting biological control of wheat pests. Conservation tillage, for example, has been shown to enhance predator communities and increase aphid predation and parasitism rates compared to conventional tillage (Tamburini et al., 2016). This practice supports more abundant and diverse natural enemy populations, which are crucial for effective pest control (De Préville et al., 2022). Additionally, intercropping systems have been found to reduce pest abundance significantly, although they do not always increase the occurrence of natural enemies (Lopes et al., 2016). Crop rotation and reduced soil disturbance also contribute to higher crop productivity and improved biological control by arthropod natural enemies. These practices collectively reduce the reliance on chemical insecticides and promote a more sustainable approach to pest management.

4.3 Interactions with native biodiversity and ecosystem health

The interactions between biological control agents and native biodiversity are essential for maintaining ecosystem health and effective pest control. Landscape-level crop diversification has been shown to enhance biological control by increasing predator and parasitoid densities, thereby reducing aphid populations in winter wheat fields (Redlich et al., 2018). However, the benefits of crop diversity can be context-dependent and may vary with landscape complexity and the presence of semi-natural habitats (Redlich, 2020). Additionally, the establishment of semi-natural habitats, such as set-aside fields, can mitigate the adverse effects of biotic homogenization and support diverse invertebrate assemblages that contribute to pest control (Figure 2) (Elek et al., 2020). These interactions highlight the importance of maintaining biodiversity and ecosystem health to support sustainable agricultural practices and effective biological control.

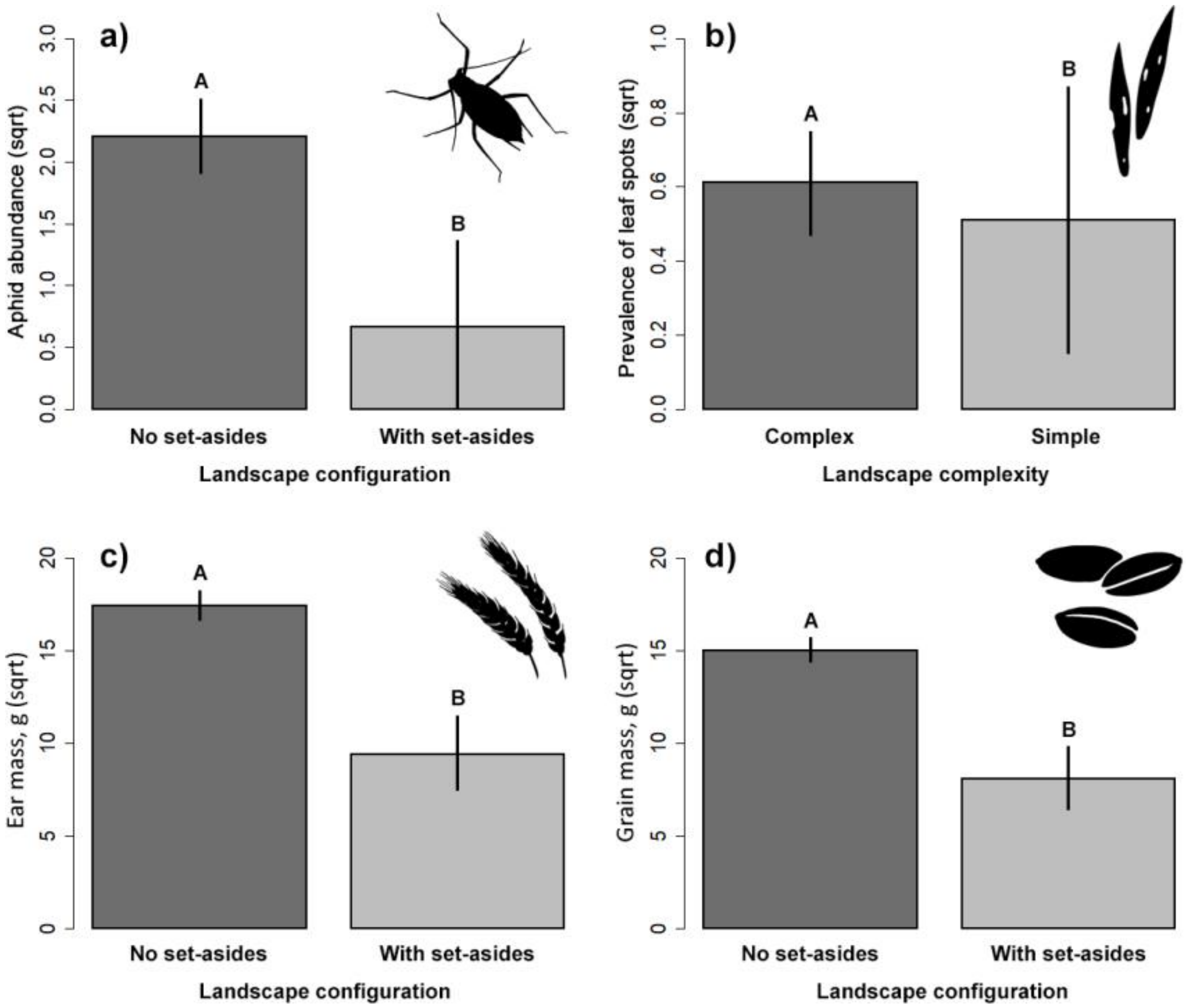

Figure 2 Response of aphid abundance (A), leaf spot prevalence (B) and winter wheat yield (C, D) to landscape configuration or complexity (Adopted from Elek et al., 2020)

Note: The yield was estimated by the ear (C) and grain (D) mass (g/m^2). The portrayed values are means with whiskers representing 95% confidence intervals. Different capital letters above indicate significant differences (Adopted from Elek et al., 2020)

5 Case Study

5.1 Implementation of biological control strategies in a specific wheat-growing region

In South East England, a comprehensive study was conducted to evaluate the economic and ecological benefits of natural pest control in wheat fields. The primary pest targeted was the grain aphid (*Sitobion avenae*), a significant threat to wheat crops in the region. Researchers implemented a natural enemy exclusion experiment to assess the impact of predators and parasitoids on aphid populations. The study found that natural enemies, including predators like hoverflies and parasitoid wasps, significantly reduced aphid populations, thereby decreasing the need for chemical insecticides (Zhang et al., 2018). Additionally, wildflower strips were introduced within wheat fields in Gembloux, Belgium, to enhance the habitat for natural enemies. This strategy successfully reduced aphid populations and supported beneficial insects such as hoverflies, which are crucial for biological pest control (Hatt et al., 2017).

5.2 Monitoring and evaluation of pest suppression outcomes

The monitoring and evaluation of pest suppression outcomes were carried out through systematic field observations and experimental setups. In South East England, the abundance of aphids and their natural enemies was monitored at both field boundaries and interiors. The presence of natural enemies was correlated with a reduction in aphid population growth, demonstrating the effectiveness of biological control (Ramsden et al., 2017). Similarly, in Belgium, the impact of wildflower strips on pest and natural enemy populations was monitored over a ten-week period. The results showed a significant reduction in aphid populations in wheat fields with wildflower strips compared to monoculture plots, highlighting the success of this biological control strategy. Furthermore, a study in Michigan evaluated the role of different natural enemy foraging guilds in regulating cereal aphid populations. The findings indicated that both foliar-foraging and ground-dwelling predators were effective in reducing aphid populations, with ground-dwelling predators being particularly impactful (Safarzoda et al., 2014).

5.3 Lessons learned and implications for broader applications

The case studies from South East England, Belgium, and Michigan provide valuable insights into the implementation and effectiveness of biological control strategies in wheat-growing regions. One key lesson learned is the importance of habitat management to support natural enemies. The introduction of wildflower strips and the promotion of landscape-level crop diversity were shown to enhance the populations of beneficial insects, leading to improved pest control (Redlich et al., 2018). Additionally, the studies highlight the need for integrated pest management (IPM) approaches that combine multiple strategies, such as crop resistance and biological control, to achieve sustainable pest suppression (Rand et al., 2020). The economic valuation of natural pest control in South East England underscores the potential cost savings and environmental benefits of reducing insecticide use through biological control. These findings suggest that broader application of these strategies could lead to more sustainable and economically viable wheat production systems globally. Future research should focus on optimizing these approaches and tailoring them to specific regional contexts to maximize their effectiveness and adoption by farmers.

6 Challenges and Limitations in Biological Control of Wheat Pests

6.1 Resistance development in pests against biological agents

One of the significant challenges in the biological control of wheat pests is the development of resistance in pests against biological control agents. For instance, the study on the ryegrass weevil pest and its parasitoid wasp in New Zealand demonstrated that over 21 years, the pest developed resistance to the parasitoid, leading to a significant decline in parasitism rates and increased pasture damage (Tomasetto et al., 2017). This resistance was not linked to environmental conditions but was specific to the most commonly grown pasture grass species, indicating that agricultural intensification and reduced biodiversity can facilitate the evolution of pest resistance. Additionally, the misguided application of chemicals in farming can stimulate pests to develop resistance, further complicating biological control efforts (Luo et al., 2023).

6.2 Economic and logistical barriers to large-scale implementation

Economic and logistical barriers also pose significant challenges to the large-scale implementation of biological control methods. Despite the inherent benefits of biological control, such as being healthier for farm workers and reducing pesticide residues, the adoption rate remains low due to several factors. These include the high costs associated with the mass production, quality control, and distribution of biological control agents (Lenteren et al., 2018). Moreover, the transition to biological control methods requires substantial initial investments and changes in farming practices, which can be economically and logistically challenging for many farmers (Baker et al., 2020). The need for increased education and extension services to promote the benefits and practical applications of biological control is crucial to overcoming these barriers.

6.3 Unintended ecological impacts of introduced biological agents

The introduction of biological control agents can also lead to unintended ecological impacts. For example, while intercropping systems have been shown to reduce pest abundance, they do not always significantly increase the occurrence of natural enemies or enhance predation and parasitism rates (Lopes et al., 2016). This indicates that the ecological balance can be disrupted, potentially leading to unforeseen consequences. Additionally, the genetic improvement of biological control agents to enhance their performance can pose risks if not carefully managed. Selecting traits for better adaptation to extreme environmental conditions or increased resistance to toxins could inadvertently affect non-target species and disrupt local ecosystems (Bielza et al., 2020). Therefore, a thorough understanding of the ecological interactions and potential impacts is essential for the sustainable implementation of biological control strategies.

7 Future Directions in Biological Control of Wheat Pests

7.1 Development of novel biocontrol agents through genetic engineering

The advancement of genetic engineering offers promising avenues for developing novel biocontrol agents (Wu, 2024). Host-induced gene silencing (HIGS) is one such strategy that has shown potential in managing diseases in wheat and barley by silencing the genes of invading pathogens (Qi et al., 2019). This transgenic approach can be tailored to target specific pests and pathogens, thereby enhancing the effectiveness and specificity of biological control methods. Additionally, the integration of entomopathogenic nematodes (EPNs) with chemical adjuvants has demonstrated increased mortality rates in pests like the wheat stem sawfly, suggesting that genetic modifications to enhance the efficacy of EPNs could be a fruitful area of research (Portman et al., 2016).

7.2 Integration of biological control with precision agriculture technologies

The integration of biological control methods with precision agriculture technologies can significantly enhance pest management in wheat production (Zhang et al., 2024). Precision agriculture allows for the targeted application of biocontrol agents, optimizing their effectiveness and reducing the need for chemical pesticides. For instance, the use of wildflower strips within wheat fields has been shown to support natural enemies of pests, thereby reducing aphid populations and the need for insecticides (Hatt et al., 2017). Similarly, organic fertilizer amendments have been found to promote wheat resistance to herbivory and enhance biocontrol services, suggesting that precision application of such amendments could further improve pest management outcomes (Gu et al., 2021).

7.3 Policy and international collaboration to promote sustainable pest management

Effective biological control of wheat pests requires robust policy frameworks and international collaboration. Policies that support the development and adoption of biocontrol agents, such as plant antagonistic bacteria and entomopathogenic fungi, can reduce reliance on chemical pesticides and promote sustainable agriculture (Abbas et al., 2017; Wakil et al., 2021). International collaboration is also crucial for sharing knowledge and resources, as demonstrated by the varying success of intercropping systems in different countries (Lopes et al., 2016). Collaborative efforts can help standardize practices, improve the efficacy of biocontrol methods, and ensure that sustainable pest management strategies are accessible to farmers worldwide.

8 Conclusion

The meta-analysis on biological control of wheat pests reveals several promising strategies for reducing pest populations and enhancing crop health. Intercropping systems have been shown to significantly reduce pest abundance, although they do not consistently increase the presence of natural enemies or predation rates. Integrated crop protection systems that combine bioagents with lower doses of fungicides have demonstrated high efficacy in controlling fungal diseases and improving wheat yield and quality. Additionally, combining host plant resistance with biological control methods, such as the use of entomopathogenic nematodes and fungi, has proven effective in managing pests like the wheat stem sawfly and Fusarium head blight. The use of plant antagonistic bacteria and allelopathic bacteria has also shown potential in controlling weed infestations and enhancing wheat growth under field conditions. Furthermore, organic fertilizer amendments have been found to promote wheat resistance to herbivory and enhance biocontrol services.

To advance biological control in wheat pest management, it is recommended to integrate multiple strategies to achieve synergistic effects. Combining intercropping with other practices that favor natural enemies can enhance pest control efficacy. Developing integrated crop protection systems that utilize bioagents in conjunction with reduced chemical inputs can improve both pest management and crop productivity. Further research should focus on optimizing the combination of host plant resistance and biological control agents to achieve sustainable pest suppression. The selection and application timing of fungal endophytes and entomopathogenic nematodes should be refined to maximize their biocontrol potential. Additionally, the use of plant antagonistic and allelopathic bacteria should be explored further to develop eco-friendly weed control methods. Finally, incorporating organic fertilizer amendments can enhance crop resistance to pests and improve biocontrol services, contributing to sustainable agricultural practices.

Biological control plays a crucial role in sustainable agriculture by reducing reliance on chemical pesticides and promoting ecological balance. The findings from this meta-analysis underscore the potential of various biological control strategies to manage wheat pests effectively while minimizing environmental impact. By integrating multiple biocontrol methods and optimizing their application, it is possible to achieve long-term pest suppression and enhance crop health. As research continues to advance, the adoption of biological control practices will be essential for developing resilient and sustainable wheat production systems.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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