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Impact of Soil Insecticides on Western Corn Rootworm and Maize Yield

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Abstract The western corn rootworm (WCR), Diabrotica virgifera virgifera LeConte, is a significant pest affecting maize (*Zea mays* L.) production, causing substantial economic losses due to root damage and yield reduction. This research examines the impact of various soil insecticides on WCR management and maize yield. Studies have demonstrated that insecticide applications, including pyrethroids, neonicotinoids, and organophosphates, significantly reduce WCR larval density and root damage, leading to increased grain yield. However, the emergence of pyrethroid-resistant WCR populations has compromised the efficacy of some soil-applied insecticides, necessitating integrated pest management (IPM) strategies to mitigate resistance development. Additionally, biological control methods, such as the use of entomopathogenic nematodes and beneficial soil organisms, have shown promise in reducing WCR populations and enhancing maize yield. Crop rotation has also been identified as an effective agronomic practice to manage WCR populations without relying on insecticides, aligning with sustainable agricultural practices. This research underscores the importance of combining chemical, biological, and cultural control methods within an IPM framework to sustainably manage WCR and optimize maize production.

Keywords Western corn rootworm (WCR); Maize yield; Soil insecticides; Integrated pest management (IPM); Biological control methods

1 Introduction

The Western Corn Rootworm (WCR) is a significant pest of maize, causing extensive damage to maize roots, which leads to plant instability, reduced growth, and substantial yield losses (Meinke et al., 2021; Ferracini et al., 2021; Furlan et al., 2022). Originating in North America, WCR has spread to Europe, becoming a serious threat to maize cultivation since the mid-1990s (Jaffuel et al., 2019; Furlan et al., 2022). The pest's larval stage is particularly destructive as it feeds on the root system, making it difficult to control with conventional pesticides (Jaffuel et al., 2019; Modic et al., 2020).

Soil insecticides have been a critical component in managing WCR populations and mitigating the damage they cause to maize crops. Historically, various classes of insecticides, including cyclodienes, organophosphates, carbamates, and pyrethroids, have been employed to control WCR (Meinke et al., 2021; Ferracini et al., 2021). However, the extensive use of these chemicals has led to the evolution of resistance in WCR populations, reducing the efficacy of these treatments (Souza et al., 2019; Meinke et al., 2021). Despite this, soil insecticides remain an essential tool, often used in combination with other management strategies such as crop rotation and the use of transgenic maize varieties expressing *Bacillus thuringiensis* (Bt) toxins (Gassmann et al., 2019; Furlan et al., 2022). Recent studies have also explored the use of beneficial soil organisms and alternative chemical treatments to enhance the effectiveness of WCR control (Jaffuel et al., 2019; Modic et al., 2020; Gyeraj et al., 2021).

This research aims to evaluate the impact of soil insecticides on WCR management and maize yield. It examines the historical and current use of soil insecticides, the development of resistance in WCR populations, and the effectiveness of various insecticide strategies; additionally, explores integrated pest management approaches that combine soil insecticides with other control methods to sustainably manage WCR and improve maize yield. By synthesizing findings from multiple studies, this research seeks to provide a comprehensive understanding of the role of soil insecticides in contemporary maize cultivation and offer insights into future directions for WCR management.

2 Biology and Behavior of Western Corn Rootworm

2.1 Lifecycle and development

The Western Corn Rootworm (WCR), is a significant pest of maize, particularly in the United States and Europe. The lifecycle of WCR includes egg, larval, pupal, and adult stages. Eggs are laid in the soil during late summer and hatch the following spring. Larvae then feed on maize roots, causing substantial damage to the plant's stability and growth. The pupal stage occurs in the soil, and adults emerge in mid-summer to feed on maize silks and leaves, completing the cycle (Figure 1) (Ferracini et al., 2021; Meinke et al., 2021).

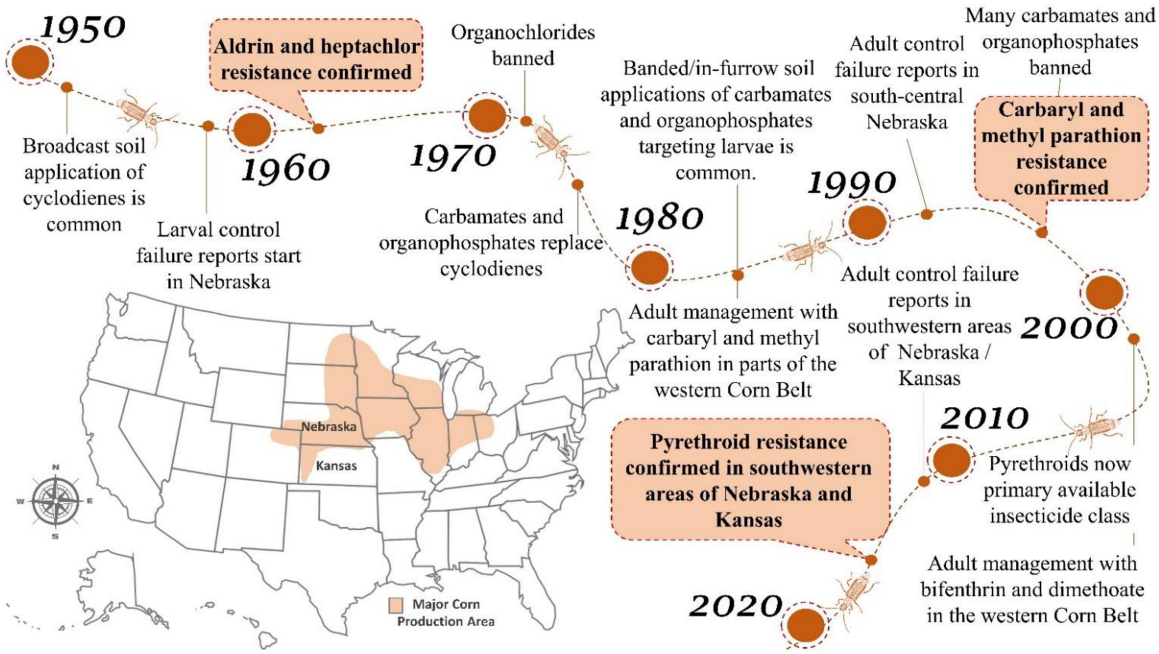

Figure 1 The agricultural region in the midwestern U.S. that is a major producer of maize is called the Corn Belt (Adopted from Meinke et al., 2021)

Image caption: This figure shows the major maize grain production area within this region, a Dvv insecticide use/field-evolved resistance timeline associated with continuous maize, and the geographic location of states Nebraska and Kansas where Dvv resistance to multiple insecticides has occurred. Maize grain production area is based on USDA-NASS 2015-2019 data (Adopted from Meinke et al., 2021)

2.2 Feeding habits and damage to maize

WCR larvae primarily feed on maize roots, which can lead to significant economic losses due to reduced plant growth and yield. The root damage caused by larval feeding can result in plant lodging, where the maize plants fall over, making harvesting difficult and further reducing yield. Adult WCRs feed on maize silks, which can interfere with pollination and further impact yield. Studies have shown that effective insecticide application at sowing can significantly reduce larval density and root damage, leading to increased grain yield (Souza et al., 2019; Ferracini et al., 2021; Nemkevich et al., 2022).

2.3 Resistance Mechanisms

The extensive use of insecticides over time has led to the development of resistance in WCR populations. Resistance mechanisms in WCR include both oxidative and hydrolytic metabolism, which facilitate cross-resistance between different classes of insecticides such as cyclodienes, organophosphates, carbamates, and pyrethroids. Field-evolved resistance has been documented, significantly reducing the efficacy of commonly used soil and foliar insecticides. This resistance can persist in field populations even in the absence of selection pressure, indicating minimal fitness costs associated with resistance (Souza et al., 2019; Meinke et al., 2021; Nemkevich et al., 2022). Integrated pest management strategies, including crop rotation and the use of multiple control tactics, are recommended to mitigate resistance development and maintain the effectiveness of insecticides (Furlan et al., 2022).

3 Soil Insecticides Overview

Soil insecticides play a crucial role in managing the western corn rootworm (WCR), Diabrotica virgifera virgifera LeConte, a significant pest of maize. These insecticides are applied to the soil to target the larval stages of WCR, which feed on maize roots, causing substantial yield losses and plant instability. The use of soil insecticides is part of an integrated pest management (IPM) strategy aimed at reducing WCR populations and mitigating damage to maize crops.

3.1 Types of soil insecticides

Several classes of soil insecticides are used to control WCR, including pyrethroids, neonicotinoids, and organophosphates. Pyrethroids, such as tefluthrin and bifenthrin, are commonly used due to their effectiveness in reducing larval density and protecting maize roots (Souza et al., 2019; Ferracini et al., 2021). Neonicotinoids, like clothianidin, are systemic insecticides that are often applied as seed treatments, providing protection as the plant grows (Ferracini et al., 2021). Organophosphates, such as tebupirimphos, are another class of insecticides used in soil applications to manage WCR populations (Souza et al., 2019).

3.2 Modes of action

The modes of action of soil insecticides vary depending on their chemical class. Pyrethroids, such as tefluthrin and bifenthrin, act on the nervous system of insects by disrupting sodium channels, leading to paralysis and death (Souza et al., 2019). Neonicotinoids, like clothianidin, target the nicotinic acetylcholine receptors in the insect nervous system, causing overstimulation and eventual death (Ferracini et al., 2021). Organophosphates, such as tebupirimphos, inhibit acetylcholinesterase, an enzyme essential for nerve function, resulting in the accumulation of acetylcholine and subsequent insect death (Souza et al., 2019).

3.3 Application methods

Soil insecticides can be applied using various methods, including in-furrow applications, seed treatments, and broadcast applications. In-furrow applications involve placing the insecticide directly into the planting furrow, providing immediate protection to the emerging seedlings (Ferracini et al., 2021). Seed treatments involve coating the seeds with insecticides before planting, offering systemic protection as the plant grows (Ferracini et al., 2021). Broadcast applications involve spreading the insecticide over the soil surface, which can then be incorporated into the soil through irrigation or rainfall (Souza et al., 2019). The choice of application method depends on factors such as the level of WCR infestation, soil type, and environmental conditions.

In conclusion, soil insecticides are a vital component of WCR management in maize production. Understanding the types, modes of action, and application methods of these insecticides can help optimize their use and improve maize yield outcomes.

4 Efficacy of Soil Insecticides on Western Corn Rootworm

4.1 Control success rates

The efficacy of soil insecticides in controlling Western Corn Rootworm (WCR) varies significantly based on the resistance levels of the WCR populations. Field trials conducted in Nebraska demonstrated that soil insecticides such as tefluthrin, bifenthrin, and a combination of cyfluthrin and tebupirimphos effectively protected maize roots from pyrethroid-susceptible WCR populations. However, their efficacy was significantly reduced in areas with pyrethroid-resistant WCR populations (Souza et al., 2019). Similarly, a three-year field experiment in Slovenia showed that tefluthrin and entomopathogenic nematodes (Heterorhabditis bacteriophora) significantly decreased the number of emerging WCR beetles, indicating effective control of WCR larvae (Figure 2) (Modic et al., 2020).

4.2 Factors influencing efficacy

Several factors influence the efficacy of soil insecticides against WCR. Resistance levels in WCR populations are a critical factor, as demonstrated by the reduced efficacy of bifenthrin and tefluthrin in pyrethroid-resistant populations (Souza et al., 2019). Additionally, environmental conditions such as soil type and pest density also play a role. For instance, the efficacy of treatments was consistent across different soil types and pest densities in Slovenia, suggesting that soil conditions did not significantly impact the effectiveness of the insecticides and nematodes used (Modic et al., 2020). Historical data also indicate that continuous maize cultivation and extensive use of insecticides contribute to the evolution of resistance in WCR populations, further complicating control efforts (Meinke et al., 2021).

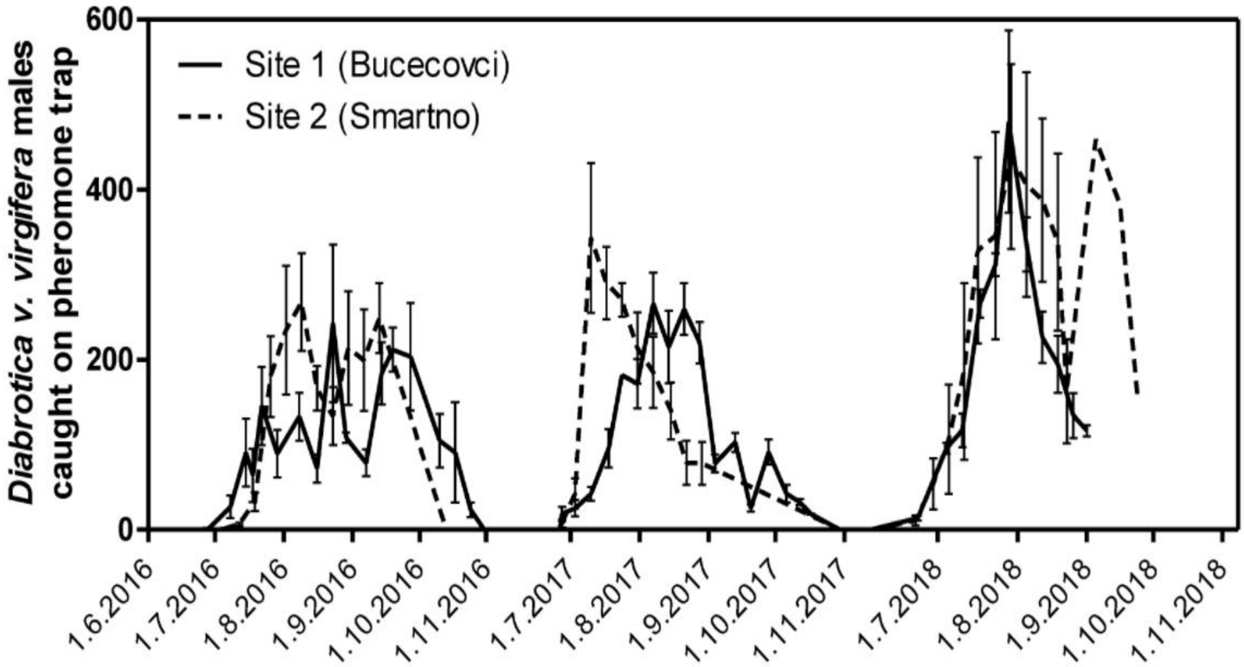

Figure 2 *Diabrotica* v. *virgifera* males caught on PAL pheromone traps 1 km away from sites 1 and 2 in 2016-2018 (Adopted from Modic et al., 2020)

Image caption: The chart shows the variation over time in the number of male western corn rootworms (*Diabrotica* v. *virgifera*) captured using pheromone traps at Bucecovci (Site 1) and Smartno (Site 2). The horizontal axis represents time, from June 2016 to November 2018, and the vertical axis represents the number of male rootworms captured. From the chart, it is evident that the number of western corn rootworms captured at both locations exhibits significant seasonal fluctuations, peaking each summer (July to September). The overall trends in the number of rootworms captured at Bucecovci and Smartno are similar over the three years, but there are some differences between specific years and months. For instance, the peak capture in Bucecovci was significantly higher than in Smartno in 2016 and 2017, whereas the data in 2018 show the opposite.(Adopted from Modic et al., 2020)

4.3 Comparison of different insecticides

Comparative studies have shown varying levels of effectiveness among different soil insecticides. In Nebraska, tefluthrin and bifenthrin were effective against susceptible WCR populations but less so against resistant ones. The combination of cyfluthrin and tebupirimphos also failed in highly resistant populations (Souza et al., 2019). In contrast, a study in Italy found that seed-applied clothianidin and tefluthrin applied at sowing significantly reduced WCR larval density and increased grain yield, highlighting their effectiveness in different settings (Ferracini et al., 2021). Additionally, the use of entomopathogenic nematodes was found to be as effective as tefluthrin in controlling WCR larvae, offering a sustainable biological control option (Modic et al., 2020).

In summary, while soil insecticides can be effective in controlling WCR, their success is highly dependent on the resistance levels of the WCR populations and environmental factors. Comparative studies suggest that integrated pest management strategies, including the use of biological controls and crop rotation, may enhance the long-term efficacy of WCR management programs.

5 Impact on Maize Yield

5.1 Yield improvement statistics

The application of soil insecticides has shown significant improvements in maize yield by effectively controlling the Western Corn Rootworm (WCR). For instance, seed-applied clothianidin and tefluthrin at sowing resulted in a maximum grain yield increase of 18% and 19%, respectively, compared to untreated controls (Ferracini et al., 2021). Similarly, treatments with tefluthrin and entomopathogenic nematodes (Heterorhabditis bacteriophora) led to a significant reduction in WCR beetle emergence and increased maize plant weights (Modic et al., 2020). In another study, the application of soil insecticides to non-Bt maize and Cry3Bb1 maize reduced adult emergence and root injury, further contributing to yield improvements (Shrestha et al., 2018).

5.2 Influence on crop quality

The quality of maize crops is also positively influenced by the use of soil insecticides. The reduction in root damage and plant lodging due to effective WCR control contributes to healthier and more robust plants. For example, the combined application of arbuscular mycorrhizal fungi, Pseudomonas bacteria, and entomopathogenic nematodes not only reduced root damage but also enhanced grain yield in treated plots (Jaffuel et al., 2019). Additionally, crop rotation strategies without insecticide use have been effective in maintaining WCR populations below damage thresholds, thereby preserving crop quality (Figure 3) (Furlan et al., 2022).

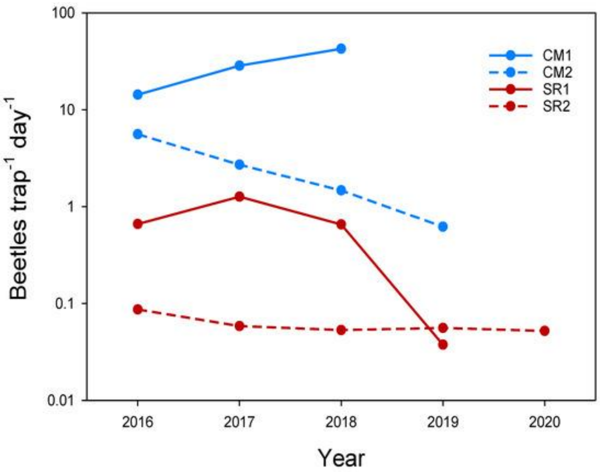

Figure 3 Effects of structural rotation (winter wheat/maize/soybean) on WCR population levels over the years (Adopted from Furlan et al., 2022)

Image caption: Numbers of WCR adults/trap/day (total sum at six weeks) in two different scenarios are shown-the first with a high percentage of continuous maize (blue lines and symbols = CM1, CM2) in Treviso province and the second based on structural rotation (red lines and symbols = SR1, SR2) at Vallevecchia pilot farm in Venice province (2016 - 2020), both in north-eastern Italy. Legend: CM1 = high presence of continuous maize with traps in continuous maize fields (Treviso); CM2 = high presence of continuous maize with traps in rotated maize fields (Treviso); SR1=extensive structural crop rotation with traps in continuous maize fields (Vallevecchia, Venice); SR2 = extensive structural crop rotation with traps in first-year maize (Vallevecchia, Venice). Numbers are two-point moving averages (Adopted from Furlan et al., 2022)

5.3 Economic benefits

The economic benefits of using soil insecticides for WCR management are substantial. By reducing yield losses and improving crop quality, farmers can achieve higher marketable yields and better returns on investment. The use of soil insecticides as part of an integrated pest management (IPM) strategy can also mitigate the evolution of resistance in WCR populations, ensuring the long-term efficacy of control measures and reducing the need for more expensive and potentially harmful interventions (Souza et al., 2019; Meinke et al., 2021). Furthermore, sustainable biological control options, such as the use of entomopathogenic nematodes, offer cost-effective alternatives to chemical insecticides, providing economic benefits while minimizing environmental impact (Modic et al., 2020; Furlan et al., 2022).

6 Environmental and Non-Target Effects

6.1 Soil health and microbial communities

The application of soil insecticides to control the western corn rootworm (WCR) can have significant impacts on soil health and microbial communities. Research has shown that the use of chemical insecticides, such as pyrethroids, neonicotinoids, and organophosphates, can alter the composition and function of soil microbial communities, potentially disrupting nutrient cycling and soil fertility (Souza et al., 2019; Ferracini et al., 2021).

Additionally, the persistence of these chemicals in the soil can lead to long-term changes in microbial diversity and activity, which are crucial for maintaining soil health and plant growth (Modic et al., 2020).

6.2 Impact on beneficial insects

Soil insecticides not only target WCR but can also affect non-target beneficial insects, including pollinators and natural predators of pests. For instance, the use of neonicotinoids has been linked to declines in bee populations, which are essential for pollination1. Moreover, beneficial soil organisms such as entomopathogenic nematodes and Pseudomonas bacteria, which can naturally control WCR populations, may also be adversely affected by chemical insecticides (Jaffuel et al., 2019). The reduction in these beneficial organisms can lead to an imbalance in the ecosystem, making crops more vulnerable to other pests and diseases (Jaffuel et al., 2019; Modic et al., 2020).

6.3 Risk of water contamination

The application of soil insecticides poses a risk of water contamination through leaching and runoff, which can carry these chemicals into nearby water bodies. This contamination can have detrimental effects on aquatic ecosystems, affecting both flora and fauna. Studies have shown that insecticides like tefluthrin and bifenthrin can persist in the environment and contaminate groundwater and surface water, posing risks to aquatic life and potentially entering the human water supply (Jaffuel et al., 2019; Meinke et al., 2021). The environmental persistence and mobility of these chemicals necessitate careful management and monitoring to mitigate their impact on water quality (Meinke et al., 2018).

7 Resistance Management Strategies

7.1 Insecticide rotation and combination

Insecticide rotation and combination are critical strategies to manage resistance in western corn rootworm (WCR). The continuous use of the same class of insecticides has led to the evolution of resistance in WCR populations. For instance, field-evolved resistance to pyrethroids, organophosphates, and carbamates has been documented, significantly reducing the efficacy of these insecticides (Souza et al., 2019; Meinke et al., 2021). Rotating insecticides with different modes of action can help mitigate resistance development. Additionally, combining insecticides with other control methods, such as Bt maize, can enhance overall pest management efficacy. However, it is essential to monitor resistance levels continuously and adjust management strategies accordingly (Souza et al., 2019; Meinke et al., 2021).

7.2 Integrated pest management (IPM)

Integrated Pest Management (IPM) is a holistic approach that combines multiple tactics to manage pest populations sustainably. For WCR, IPM strategies include crop rotation, use of resistant hybrids, biological control, and judicious use of insecticides. Crop rotation, in particular, has been shown to be highly effective in reducing WCR populations and minimizing damage without relying solely on insecticides (Furlan et al., 2019). Implementing IPM can delay resistance development and reduce the environmental impact of chemical controls. Studies have demonstrated that IPM practices, such as rotating crops and integrating biological controls, can maintain WCR populations below economic thresholds, thereby reducing the need for insecticides (Furlan et al., 2019; Meinke et al., 2021).

7.3 Genetic approaches and biotechnology

Genetic approaches and biotechnology offer promising solutions for managing WCR resistance. Transgenic maize expressing Bt toxins, such as Cry3Bb1 and Cry34/35Ab1, has been widely adopted to control WCR. However, resistance to these Bt traits has emerged, necessitating the development of new strategies (Shrestha et al., 2018; Furlan et al., 2019; Reinders et al., 2021). Pyramiding multiple Bt genes in a single hybrid can provide more robust protection against WCR by targeting different mechanisms of action. Additionally, ongoing research into novel Bt toxins and other genetic modifications aims to enhance resistance management. The use of genetically engineered crops should be integrated with other IPM practices to ensure long-term sustainability and effectiveness (Shrestha et al., 2018; Furlan et al., 2019; Reinders et al., 2021).

By employing a combination of insecticide rotation, IPM, and genetic approaches, it is possible to manage WCR resistance effectively and sustain maize yield. Continuous monitoring and adaptation of these strategies are essential to address the evolving resistance patterns in WCR populations.

8 Advances in Research and Technology

8.1 New insecticidal compounds

Recent studies have highlighted the development and evaluation of new insecticidal compounds to manage the western corn rootworm (WCR), Diabrotica virgifera virgifera LeConte. For instance, research has shown that soil-applied insecticides such as tefluthrin and bifenthrin can effectively protect maize roots from WCR damage, although their efficacy is significantly reduced in populations exhibiting pyrethroid resistance (Souza et al., 2019). Additionally, the use of neonicotinoids like clothianidin has been found to significantly reduce WCR larval density and increase grain yield when applied as seed treatments (Ferracini et al., 2021). The exploration of alternative compounds, such as entomopathogenic nematodes, has also shown promise, with studies indicating that Heterorhabditis bacteriophora can be as effective as traditional insecticides like tefluthrin in controlling WCR larvae (Modic et al., 2020).

8.2 Precision agriculture and application techniques

Advancements in precision agriculture have led to more targeted and efficient application techniques for insecticides. The integration of precision agriculture tools allows for the precise application of insecticides, reducing the overall amount used and minimizing environmental impact. For example, the use of soil conditioners in combination with entomopathogenic nematodes has been shown to enhance the effectiveness of biological control methods, providing a sustainable alternative to chemical insecticides (Modic et al., 2020). Additionally, the application of insecticides at sowing, either as seed treatments or in-furrow applications, has been demonstrated to significantly reduce WCR larval density and improve maize yield (Ferracini et al., 2021).

8.3 Monitoring and resistance detection

Effective monitoring and early detection of resistance are crucial for managing WCR populations and mitigating the impact of resistance on maize yield. Studies have shown that field-evolved resistance to various insecticides, including pyrethroids and *Bacillus thuringiensis* (Bt) traits, is a significant challenge in WCR management (Gassmann et al., 2019; Meinke et al., 2021). Monitoring programs that assess WCR susceptibility to different insecticides can help in the timely detection of resistance and inform management strategies. For instance, laboratory dose-response bioassays have been used to confirm resistance levels and guide the selection of appropriate insecticides for field application1. Additionally, integrated pest management (IPM) approaches that combine chemical, biological, and cultural control methods are recommended to manage resistance and prolong the effectiveness of available insecticides (Meinke et al., 2021; Furlan et al., 2022).

By leveraging these advances in research and technology, it is possible to develop more effective and sustainable strategies for managing WCR and protecting maize yield.

9 Challenges and Future Directions

9.1 Barriers to effective control

The control of the Western Corn Rootworm (WCR) faces several significant barriers. One of the primary challenges is the development of resistance to various classes of insecticides, including pyrethroids, organophosphates, and carbamates, which has been documented over several decades (Souza et al., 2019; Meinke et al., 2021). This resistance reduces the efficacy of traditional chemical control methods, necessitating the development of new strategies. Additionally, the persistence of resistance even in the absence of selection pressure suggests minimal fitness costs associated with resistance traits, complicating management efforts (Meinke et al., 2021). Another barrier is the limited effectiveness of certain insecticides under field conditions, particularly in areas with high levels of resistance (Souza et al., 2019). Furthermore, the environmental impact and regulatory restrictions on the use of certain insecticides pose additional challenges to effective WCR management (Furlan et al., 2022).

9.2 Areas for further research

Future research should focus on several key areas to improve WCR management. There is a need for the development and evaluation of new insecticides with novel modes of action to overcome existing resistance3. Additionally, research into integrated pest management (IPM) strategies that combine chemical, biological, and cultural control methods is crucial. For instance, the use of entomopathogenic nematodes and beneficial soil organisms, such as arbuscular mycorrhizal fungi and Pseudomonas bacteria, has shown promise in reducing WCR damage and should be further explored (Jaffuel et al., 2019; Modic et al., 2020). Another important area is the investigation of crop rotation and other agronomic practices to reduce WCR populations without relying solely on chemical controls (Furlan et al., 2022). Finally, understanding the mechanisms of resistance and developing molecular tools for early detection of resistance can help in designing more effective management strategies (Gassmann et al., 2019).

9.3 Policy and regulatory considerations

Policy and regulatory frameworks play a critical role in the management of WCR. There is a need for policies that support the adoption of IPM practices and the development of sustainable pest management solutions. Regulations should encourage the use of environmentally friendly and non-chemical control methods, such as biological control agents and crop rotation (Modic et al., 2020; Furlan et al., 2022). Additionally, policies should promote research and development of new insecticides and resistance management strategies. Regulatory agencies must also ensure that new products are thoroughly evaluated for their efficacy and environmental impact before approval. Furthermore, there should be guidelines for the responsible use of insecticides to delay the development of resistance and preserve the effectiveness of existing control measures (Souza et al., 2019; Meinke et al., 2021). Collaboration between policymakers, researchers, and farmers is essential to implement these strategies effectively and ensure the long-term sustainability of maize production.

10 Concluding Remarks

The research on the impact of soil insecticides on Western Corn Rootworm (WCR) and maize yield has provided several key insights. Various chemical control strategies, including pyrethroids, neonicotinoids, and organophosphates, have been shown to significantly reduce WCR larval density and root damage, leading to increased grain yield. Studies have also demonstrated that soil-applied granular insecticides and seed treatments can effectively manage WCR populations, although resistance to pyrethroids has been observed, reducing the efficacy of these treatments in some regions. Additionally, biological control methods, such as the use of entomopathogenic nematodes and beneficial soil organisms, have shown promise as sustainable alternatives to chemical insecticides.

The importance of sustainable insecticide use cannot be overstated. The history of WCR management has shown that over-reliance on chemical insecticides can lead to resistance, rendering these treatments less effective over time. Integrated Pest Management (IPM) strategies, which combine chemical, biological, and cultural control methods, are essential for sustainable WCR management. Crop rotation, for example, has been identified as an effective strategy to keep WCR populations below damage thresholds without the need for insecticides, thereby reducing environmental impacts and promoting long-term agricultural sustainability.

In conclusion, while soil insecticides play a crucial role in managing WCR and protecting maize yield, their use must be balanced with sustainable practices to prevent resistance development and environmental harm. Future research should focus on enhancing the efficacy of biological control agents and integrating them into IPM frameworks. Additionally, continuous monitoring of WCR resistance levels and adapting management strategies accordingly will be vital. Policymakers and agricultural stakeholders should promote the adoption of IPM practices and support research into sustainable pest management solutions to ensure the long-term viability of maize production.

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Conflict of Interest Disclosure

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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