A REVIEW OF ALTERNATIVE METHODS FOR CONTROLLING THE MAIZE LEAF WEEVIL (*TANYMECUS DILATICOLLIS*) IN THE CONTEXT OF PESTICIDE RESTRICTIONS

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Abstract

The maize leaf weevil (Tanymecus dilaticollis Gyll., Coleoptera: Curculionidae) stands as one of the most damaging pests of maize in Romania and Eastern Europe. Historically, its control largely relied on neonicotinoid-based seed treatments. However, EU restrictions on these substances have made effective management increasingly challenging. This review critically examines alternative control strategies, including entomopathogenic fungi (Beauveria bassiana, Metarhizium anisopliae), microbial biopesticides (Bacillus thuringiensis), botanical extracts (e.g., neem oil), and agroecological approaches like crop rotation. It also explores the burgeoning role of kairomone-based traps and emerging sensor technologies for improved monitoring and early warning systems. While these methods show promise, their efficacy often depends on environmental conditions and application techniques, and their economic viability needs further assessment. The findings underscore the critical importance of integrating these alternatives into a robust Integrated Pest Management (IPM) strategy for sustainable maize protection, emphasizing the urgent need for enhanced monitoring tools, comprehensive economic evaluations, and farmer-ready solutions.

Keywords: *Tanymecus dilaticollis, neonicotinoid alternatives, entomopathogenic fungi, biopesticides, botanical extracts, kairomones, IPM, sensor monitoring, precision agriculture, economic viability*

1. INTRODUCTION

Maize (*Zea mays* L.) holds substantial economic importance both globally and within the European Union (EU), serving as a major source of food, animal feed, and bio-industrial raw materials. Romania, the leading maize producer in the EU, annually cultivates between 2.3 and 2.6 million hectares, surpassing other major producers such as France and Hungary (Jurjescu et al., 2020; Ona et al., 2021; Chiurciu et al., 2022). Yields in Romania vary considerably depending on climatic conditions and agronomic practices, with national averages around 4 tons per hectare, while optimal field trials have reported yields ranging between 5 and 11 tons per hectare (Giucă & Motofeanu, 2022; Grigor & Sala, 2024).

Effective pest and disease management remains essential to ensure maize productivity, profitability, and food security. Among the most destructive pests in Eastern Europe is *Tanymecus dilaticollis* Gyll. (Coleoptera: Curculionidae), commonly referred to as the maize leaf weevil. This pest primarily damages maize during its early vegetative stages (BBCH 10–14), causing foliar injuries that may result in seedling mortality, reduced plant vigor, and diminished yield potential (Georgescu et al., 2017; 2023). Severe outbreaks have been documented, particularly during drought years, such as 2012 and 2014, affecting both maize and sunflower crops (Georgescu et al., 2013; 2015; 2017).

Historically, *T. dilaticollis* was effectively managed through systemic neonicotinoid seed treatments, including imidacloprid, clothianidin, and thiamethoxam (Georgescu et al., 2019; Jactel et al., 2019). These treatments provided consistent prophylactic protection during early growth stages, reducing the need for foliar applications and ensuring early crop establishment. However, due to growing concerns about environmental and health impacts, particularly their effects on pollinators, the EU progressively restricted and ultimately banned these substances (Ihara & Matsuda, 2018; Jactel et al., 2019; Georgescu et al., 2021). This regulatory shift has led to elevated pest pressure, increased production costs, and a marked reduction in available chemical control options, thereby emphasizing the urgent need for alternative management approaches (Kathage et al., 2017; Amuza et al., 2021).

In line with the European Green Deal and the Farm to Fork Strategy, which aim for a 50% reduction in pesticide use and risk by 2030, there is a strong policy-driven emphasis on developing sustainable pest management alternatives (Montanarella & Panagos, 2021; Pilvere et al., 2024; Alexoaei et al., 2022).

Although significant progress has been made, several knowledge gaps continue to hinder the widespread adoption of these alternatives for *T. dilaticollis* management. In particular, there is an urgent need for more consistent field validation across diverse environments, comprehensive economic analyses of integrated strategies, and the development of practical, farmer-friendly decision support systems incorporating advanced monitoring technologies. This review synthesizes current knowledge on alternative control methods and identifies key research priorities and future directions essential for achieving sustainable and effective *T. dilaticollis* management in maize production systems.

2. BIOLOGY, ECOLOGY, AND ECONOMIC IMPACT OF *TANYMECUS DILATICOLLIS*

Tanymecus dilaticollis Gyll. (Coleoptera: Curculionidae), also referred to as the maize leaf weevil or grey maize weevil, is a significant pest of maize (*Zea mays* L.) and sunflower (*Helianthus annuus* L.) in Eastern Europe (Toshova et al., 2021). It belongs to a family of beetles with numerous economically important phytophagous species (Papadopoulou, 2012; Takov et al., 2013; Talwar, 2014; Candan et al., 2020; Fătu et al., 2023; Toshova et al., 2024).

Although polyphagous, the species exhibits a strong preference for maize and sunflower, particularly under the agroclimatic conditions of Romania and Bulgaria (Georgescu et al., 2020; 2021; Toshova et al., 2021; Fătu et al., 2023). It is among the most destructive maize pests in this region, especially when infestations coincide with early crop development (Georgescu et al., 2021; Toshova et al., 2024).

Damage is most severe from seedling emergence through the four-leaf stage (BBCH 10–14). Adults feed on cotyledons and young leaves, sometimes destroying entire seedlings. Without seed treatments, infestation can cause high mortality rates (Georgescu et al., 2017; 2018; 2020; 2021; 2023). Attack severity is typically rated on a visual scale from 1 (no visible damage) to 9 (complete destruction), with values above 6 frequently reported in untreated field plots (Georgescu et al., 2017; 2023).

Consequences often result in stand loss, stunted growth, and diminished plant vigor. In heavily infested fields, over 90% of seedlings may be destroyed, often necessitating reseeded and causing considerable economic loss (Georgescu et al., 2023). For example, Petcu et al. (2023) reported a stark difference: 16–19% injury in untreated plots compared to only 6–11% where seed treatments were applied. This clearly demonstrated the critical importance of prophylactic chemical control (which was historically available through neonicotinoids) in mitigating *T. dilaticollis* damage. Beyond direct feeding, weakened plants are more vulnerable to diseases and abiotic stress, compounding yield losses (Petcu et al., 2023).

Infestation levels are strongly influenced by spring weather conditions. Warm, dry springs with more than 10 consecutive days without rainfall are associated with increased pest activity (Georgescu et al., 2014; 2017; 2021; 2023). Contrary to earlier assumptions, mild winters are not reliable predictors of spring outbreaks (Georgescu et al., 2017). The critical factors remain drought, limited precipitation, and host phenology (Pintilie et al., 2023). Under greenhouse conditions at NARDI Fundulea, *T. dilaticollis* exhibited an attack intensity of 8.75 on untreated plants, confirming its high feeding potential under optimal temperatures (Georgescu et al., 2023).

Agronomic practices such as continuous maize or sunflower monoculture contribute to population buildup in the soil, increasing infestation risk (Georgescu et al., 2020; 2021). In high-pressure years, untreated seedlings are often destroyed soon after emergence (Georgescu et al., 2023).

In Romania, several major outbreaks of *T. dilaticollis* have been recorded over the past decades, with attack intensities ranging from moderate to extremely severe. These outbreaks were generally associated with climatic conditions favoring overwintering survival and spring feeding activity. Table 1 summarizes historical outbreaks and their associated climatic parameters based on long-term field observations at Fundulea and more recently at Sopema farm in southeastern Romania (Georgescu et al., 2015; 2017; 2019; 2021).

Year	Location	Attack Intensity (1–9)	Winter Temperature Deviation (°C)	Spring Rainfall Deviation (mm)	Citation(s)
1985	Fundulea	8.9	+5.0	-36.1	Georgescu et al., 2015
1986	Fundulea	8.0	+1.6	-20.5	Georgescu et al., 2015
1988	Fundulea	8.0	+4.6	-30.4	Georgescu et al., 2015
1989	Fundulea	9.0	+0.4	-30.6	Georgescu et al., 2015; Georgescu et al., 2017
1994	Fundulea	8.7	+0.8	n.a.	Georgescu et al., 2015
1995	Fundulea	8.4	+1.3	+54.6	Georgescu et al., 2015; Georgescu et al., 2017
2003	Fundulea	7.8	-2.4	-32.4	Georgescu et al., 2015; Georgescu et al., 2017
2011	Fundulea	5.8	+0.4	+30.5	Georgescu et al., 2015
2014	Fundulea	5.91	+1.4	-22.2	Georgescu et al., 2015
2014	Mărculești	5.94	n.a.	n.a.	Georgescu et al., 2015
2018	SE Romania (Sopema farm, Ialomița)	8.05	Spring warmer	~ -72.8	Georgescu et al., 2019
2020	SE Romania (Sopema farm, Ialomița)	4.47	~ -5.0	-38.0	Georgescu et al., 2021

Table 1. Years with major *T. dilaticollis* outbreaks in Romania and associated climatic conditions

The analysis of long-term data indicates that severe *T. dilaticollis* outbreaks are frequently associated with mild winters combined with spring rainfall deficits, which create favorable conditions for adult survival and feeding (Georgescu et al., 2015; 2017; 2019; 2021). However, exceptions such as 1995 and 2011 suggest that additional factors beyond temperature and precipitation may influence pest dynamics. Recent field observations at Sopema farm reinforce this pattern: severe outbreaks were recorded in 2018 under warmer, drier spring conditions (Georgescu et al., 2019), while low temperatures in spring 2020 limited adult activity, resulting in significantly lower attack intensities despite rainfall deficits (Georgescu et al., 2021). These findings highlight the complex interaction between climatic variability and *T. dilaticollis* population dynamics.

3. IMPACT OF PESTICIDE RESTRICTIONS IN THE EU ON *TANYMECUS DILATICOLLIS* CONTROL

For decades, the control of *T. dilaticollis* in Eastern Europe relied heavily on prophylactic chemical strategies, primarily neonicotinoid seed treatments. These systemic insecticides: imidacloprid, clothianidin, and thiamethoxam, provided reliable protection during early crop stages (BBCH 10–14), minimizing the need for foliar sprays (Georgescu et al., 2014; 2019; 2021; Matsuda, 2024).

Alternative insecticides, such as pyrethroid-based foliar sprays (e.g., deltamethrin, cypermethrin, lambda-cyhalothrin) and other neonicotinoids like acetamiprid and thiacloprid, have been tested. However, they have largely failed to replicate the systemic efficacy of the banned seed treatments (Georgescu et al., 2019; 2021).

Driven by mounting evidence of environmental risks, particularly concerning pollinator health, the EU initiated a progressive regulatory phase-out. In 2013, restrictions were imposed on the use of imidacloprid, clothianidin, and thiamethoxam for bee-attractive crops (Dewar, 2016; Blacquière & Van Der Steen, 2017). France expanded its national ban in 2016 to cover all five major neonicotinoids, and in 2019, the EU implemented a complete prohibition on their outdoor use, including on maize, thus eliminating a cornerstone of *T. dilaticollis* control (Georgescu et al., 2021; Ihara & Matsuda, 2018; Vojvodić & Bažok, 2021).

These regulatory changes have profoundly affected pest control. In Romania, no chemical alternative has fully restored the efficacy previously achieved with neonicotinoid seed treatments. Biological agents (e.g., *Beauveria bassiana*), botanical extracts (e.g., neem oil), and contact insecticides (e.g., thiacloprid, cyantraniliprole) have shown limited performance, particularly under high pest pressure (Georgescu et al., 2016; 2019; Toshova et al., 2021; Fătu et al., 2023).

Producers now face elevated input costs and sustained pest threats. In untreated or insufficiently protected fields, seedling mortality may reach 90% under favorable pest conditions (Georgescu et al., 2021; Amuza et al., 2021). Consequently, pyrethroid use has increased, despite their reduced systemic action and higher risks of resistance development (Kathage et al., 2017).

These developments reflect broader shifts in EU agricultural policy. The Green Deal (2019) and Farm to Fork Strategy aim to cut pesticide use and associated risks by 50% by 2030. National action plans and Common Agricultural Policy (CAP) reforms now encourage Integrated Pest Management (IPM), non-chemical alternatives, and transitions toward organic and precision farming (Triantafyllidis et al., 2023; Lesecq et al., 2022). The EU has also strengthened surveillance through initiatives such as the EU Soil Observatory (Orgiazzi et al., 2022). Between 2018 and 2023, 14 insecticidal substances were banned, contributing to a cumulative total of 118 active substances withdrawn since 2011, mainly due to concerns regarding carcinogenicity, reproductive toxicity, and environmental persistence (Marchand, 2022; Spyrakis & Dragani, 2023; Gensch et al., 2024).

While these measures are intended to enhance biodiversity and protect human health, their rapid implementation in the absence of consistently effective and economically viable alternatives has disrupted pest management practices. Farmers increasingly rely on foliar sprays, elevated sowing densities, and intensive monitoring, which raise costs without fully guaranteeing crop protection (Hillocks, 2012; Amuza et al., 2021). Moreover, biological alternatives often fail to deliver the reliability of neonicotinoids, particularly under the high pest pressures characteristic of Southeastern Europe. The substitution of neonicotinoids with compounds posing similar risks remains a significant concern (Marchand, 2022). The case of *T. dilaticollis* illustrates the gap between regulatory objectives and practical field-level implementation. Achieving EU targets will require substantial investment in research, innovation, and the development of robust, farmer-ready IPM solutions that are both ecologically sustainable and agronomically effective.

4. ALTERNATIVE BIOLOGICAL AND BOTANICAL CONTROL METHODS FOR *TANYMECUS DILATICOLLIS*

The EU-wide ban on neonicotinoid seed treatments has significantly constrained chemical control options for *T. dilaticollis*. As a result, various alternative approaches, including biological agents, botanical products, microbial biopesticides, and agroecological strategies, have been extensively investigated in both laboratory and field trials. Although none fully replicate the systemic protection provided by neonicotinoids, several demonstrate considerable promise, particularly when incorporated into integrated management systems.

4.1 Biological Control: Entomopathogenic Fungi and Nematodes

Entomopathogenic fungi (EPF), especially *Beauveria bassiana*, *B. pseudobassiana*, and *Metarhizium anisopliae*, represent effective biological alternatives against *T. dilaticollis*. Their infection process involves spore attachment to the insect cuticle, enzymatic penetration (via proteases and chitinases), internal fungal proliferation, toxin production, and ultimately host death within approximately 2–7 days

(Ozdemir et al., 2020; Shehzad et al., 2021; Figueroa et al., 2024). Laboratory trials using commercial products such as Naturalis® (based on *B. bassiana*) reported near-total pest mortality, accompanied by rapid incapacitation (Toshova et al., 2021; Fătu et al., 2023; Georgescu et al., 2023). However, field performance remains inconsistent, largely due to environmental variability, particularly temperature and humidity requirements for optimal fungal germination and infection (Razinger et al., 2020; Liu et al., 2022; Idrees et al., 2023). For example, *M. anisopliae* exhibited limited field efficacy, with mortality rates around 10%, highlighting the need for optimized application techniques or strain selection to improve field persistence and control levels (Georgescu et al., 2023).

Entomopathogenic nematodes (EPNs), particularly *Steinernema carpocapsae*, have also shown promising results. Powder formulations such as Nemastar® demonstrated high laboratory efficacy (>94% mortality) and substantial yield improvements when combined with biological seed treatments, significantly outperforming alternatives like *Heterorhabditis bacteriophora* (Toshova et al., 2024). These findings emphasize the potential role of EPNs as key components in sustainable management programs for *T. dilaticollis*, especially with improved formulations that enhance their field applicability.

4.2 Microbial Biopesticides and Botanical Products

Microbial biopesticides, particularly *Bacillus thuringiensis* (Bt), have been employed through seed or foliar applications in organic maize systems, generally exhibiting moderate efficacy. However, their performance improves substantially when combined with other biological agents, underlining the importance of synergistic interactions for practical implementation (Toader et al., 2020).

Botanical insecticides, notably neem-based products and spinosad (derived from *Saccharopolyspora spinosa*), have also been widely tested. Neem oil applied as a seed treatment protected up to 82.8% of plants in organic field trials, while laboratory assays using azadirachtin (NeemAzal T/S®) reported adult mortality rates ranging from 6% to 44%, indicating inconsistent efficacy under high pest pressure (Toader et al., 2020; Toshova et al., 2021). By contrast, spinosad has consistently demonstrated higher protection, preserving up to 80% of plants when applied during early maize growth stages. Nevertheless, both neem oil and spinosad require frequent applications due to their short residual activity, which may increase operational costs (Iglesias et al., 2021; Choudhary et al., 2024).

4.3 Agroecological Strategies and Combined Applications

Agroecological methods further enhance pest control by integrating multiple cultural and biological tactics. For instance, biostimulants such as *Bacillus subtilis* and *Trichoderma harzianum* (commercialized as BioZeaFert), combined with crop rotation, cover crops, and organic amendments, have significantly reduced *T. dilaticollis* damage to 6–11%, compared to 16–19% in untreated monocultures (Petcu et al., 2023).

Recent studies also highlight the potential of plant-derived synthetic volatiles (kairomones) in pest monitoring. Electrophysiological studies revealed strong adult weevil responses to green leaf volatiles, particularly (E)-2-hexen-1-ol and (Z)-3-hexen-1-ol, leading to improved trap captures under field conditions. These kairomone-based traps can facilitate early pest detection and support timely intervention decisions within IPM frameworks (Toshova et al., 2010).

4.4 Advances in Formulation Technologies for Biological Agents

Recent technological advancements in biological control formulations have significantly improved practicality and efficacy. Notably, powder formulations of entomopathogenic nematodes (*S. carpocapsae*) have proven highly effective, achieving substantial pest mortality and yield enhancements in maize cultivation (Toshova et al., 2024). Additionally, new microencapsulation methods employing biopolymers are enhancing stability, shelf-life, and controlled release of microbial biological control agents, thereby increasing their reliability and applicability under varied field conditions (Saberi-Riseh et al., 2021).

A comparative overview of alternative methods tested against *T. dilaticollis* is presented in Table 2.

Method / Agent	Laboratory Efficacy	Field / Greenhouse Efficacy	Notes	Citation(s)
***Beauveria bassiana* (Naturalis®)**	High (up to 100%)	Variable, sometimes low	Fast-acting in lab, less consistent in field	Fătu et al., 2023; Toshova et al., 2021; Georgescu et al., 2023
Neem oil / NeemAzal T/S®	Low to Moderate	Up to 81.30% plants saved	More effective as seed treatment	Toader et al., 2020; Toshova et al., 2021
Spinosad	Moderate	Up to 78.99% plants saved	Applied during vegetation period	Toader et al., 2020
Bacillus thuringiensis	Not reported	Up to 78% plants saved	Used in organic systems	Toader et al., 2020
***Steinernema carpocapsae* (Nemastar®)**	Very high (>94%)	Effective, yield increase	Best results with biological seed treatment	Toshova et al., 2024
Bacillus subtilis / T. harzianum	Not reported	Reduced damage (6–11%)	Effective with agroecological practices	Petcu et al., 2023

Table 2. Comparative Efficacy of Alternative Control Methods for *Tanymecus dilaticollis*

The results presented in Table 2 clearly demonstrate that while several alternative methods exhibit high efficacy under laboratory conditions, field performance remains variable, often influenced by environmental factors and application methods. These findings underscore the necessity of integrating multiple approaches within an IPM framework to ensure effective and sustainable management of *T. dilaticollis*.

5. INTEGRATED PEST MANAGEMENT STRATEGY FOR *TANYMECUS DILATICOLLIS*

The removal of neonicotinoid seed treatments from the European market has significantly constrained *T. dilaticollis* management, particularly during maize's early vegetative stages. Previously, these systemic insecticides, imidacloprid, thiamethoxam, and clothianidin, offered consistent and effective field-level protection (Georgescu et al., 2019; 2021). In the current regulatory and agronomic context, the development and implementation of comprehensive IPM strategies have become essential. IPM combines multiple control tactics (chemical, biological, botanical, and agroecological), guided by monitoring and economic thresholds, to sustainably suppress pest populations while minimizing environmental and economic risks.

5.1. Pest Monitoring and Early Warning Systems

At the core of any successful IPM approach lies the accurate monitoring of pest populations and the application of clearly defined economic thresholds. For *T. dilaticollis*, regular field monitoring is particularly important during the maize growth stages BBCH 10–14, when the crop is most susceptible to weevil feeding. Studies have consistently shown that adult weevils cause the greatest damage during this period, often leading to stand losses and growth suppression (Georgescu et al., 2014; 2017; 2019; Amuza et al., 2021). Based on field data and regional experience, an economic threshold of 4–5 adults per square meter has been established; surpassing this density typically results in economically significant damage, necessitating the prompt initiation of control measures (Amuza et al., 2021).

Traditional monitoring employs visual scouting and pitfall traps. However, the often-rapid outbreak dynamics of *T. dilaticollis*, triggered by warm, dry springs, necessitate the implementation of more proactive, precise, and technologically advanced early warning systems. Emerging sensor technologies offer several promising innovations:

- Automated traps integrated with image recognition: Kairomone-based traps, utilizing attractants such as (E)-2-hexen-1-ol and (Z)-3-hexen-1-ol (Toshova et al., 2010), can be equipped with low-power cameras and artificial intelligence (AI) algorithms that autonomously capture, identify, and count trapped individuals, transmitting real-time population data. These systems minimize labor requirements and provide timely population assessments, facilitating early intervention (Liu et al., 2021; Kim et al., 2020).
- Environmental sensors: Real-time meteorological data (temperature, humidity, soil moisture) from in-field sensors can feed into predictive models to forecast pest emergence. Given the strong correlation between warm, dry springs and elevated *T. dilaticollis* activity (Georgescu et al., 2014; 2017; 2021; 2023), such data improve outbreak forecasting (Oguz et al., 2024).
- Remote sensing (drones and satellites): Although unable to directly detect *T. dilaticollis*, drones with multispectral or thermal imaging, as well as satellite platforms like Sentinel-2, can monitor crop vigor and detect early stress symptoms linked to pest damage. Machine learning algorithms applied to these datasets allow for spatially targeted scouting and interventions, improving resource efficiency (Yang & Suh, 2023; Gul & Banday, 2024).
- Integrated Decision Support Systems (DSS): The ultimate goal is to combine data from automated traps, environmental sensors, and remote sensing into comprehensive digital decision support systems. These platforms can process vast amounts of data, alert farmers when economic thresholds are approached, and recommend appropriate, localized control measures based on integrated IPM principles. Such systems are crucial for bridging the gap between raw monitoring data and actionable advice, empowering farmers to make timely and informed decisions for optimal pest management (Yuan et al., 2023; Sridevy, Devi & Sankar, 2023).

Although the widespread deployment of these advanced monitoring systems for *T. dilaticollis* is still evolving, their integration represents a critical component of future IPM frameworks, offering the responsiveness needed to compensate for the loss of systemic seed treatments.

5.2. Control Methods and Their Integration

Neonicotinoid seed treatments previously served as the cornerstone of *T. dilaticollis* management. Following their ban, pest control has shifted toward a combination of foliar insecticides, biological agents, botanical products, and agroecological measures.

Foliar insecticides, including acetamiprid and deltamethrin, have been employed with limited success. Their effectiveness decreases under high pest pressure or when not combined with seed treatments (Georgescu et al., 2014; 2019; 2021), limiting their standalone reliability during early crop development.

Biological control has gained attention as a promising alternative. Entomopathogenic fungi, particularly *Beauveria bassiana*, have exhibited strong efficacy under laboratory conditions; however, environmental variability (temperature, soil moisture) frequently limits their field performance (Toshova et al., 2021; Fătu et al., 2023). Entomopathogenic nematodes, especially *Steinernema carpocapsae* (Nemastar®), have demonstrated superior performance, reducing pest populations and enhancing plant survival, particularly when combined with biological seed treatments (Toshova et al., 2024).

Botanical insecticides, such as neem oil and spinosad, approved for organic agriculture, have also proven useful. Neem oil seed coatings have achieved up to 83% plant protection in field trials, while spinosad has provided moderate control when applied during early vegetative stages (Toader et al., 2020).

Agroecological practices provide further pest suppression benefits. Crop rotation, cover cropping, and organic soil amendments enriched with microbial biostimulants (*Bacillus subtilis*, *Trichoderma harzianum*) disrupt *T. dilaticollis* life cycles while improving overall plant and soil health (Petcu et al., 2023). Studies integrating these diverse approaches report improved pest suppression and higher maize survival rates (Toader et al., 2020; Petcu et al., 2023; Toshova et al., 2024).

5.3. Role of IPM in Resistance Management

One of IPM's key advantages is its ability to delay or prevent insecticide resistance development. Calendar-based pesticide applications exert continuous selection pressure, accelerating resistance. In contrast, IPM minimizes unnecessary insecticide use by applying treatments only when thresholds are exceeded, thereby reducing selection pressure (Caprio, 1998; Bass & Jones, 2018; Green et al., 2020).

Threshold-based interventions combined with the establishment of untreated refuges help maintain susceptible pest populations, diluting resistance alleles across the broader population, a strategy supported by population genetics models (Caprio, 1998). Moreover, conserving and enhancing natural enemies (predators, parasitoids) can reduce pest densities and limit reliance on chemical interventions, further suppressing resistance development (Liang et al., 2018).

From both evolutionary and agronomic perspectives, combining diverse control tactics within an IPM framework enhances long-term sustainability, preserves existing control tools, and extends their efficacy across growing seasons (Green et al., 2020).

5.4. Challenges and Future Directions

Despite the conceptual strengths of IPM, multiple challenges hinder its full implementation for *T. dilaticollis*. A major limitation is the discrepancy between laboratory efficacy and field performance of biological and botanical products. Environmental variability, including soil properties, moisture levels, temperature fluctuations, and pest behavior, can severely affect outcomes (Fătu et al., 2023; Georgescu et al., 2023). Consequently, many growers remain hesitant to adopt unvalidated alternatives under their specific farm conditions.

A second major constraint is the lack of comprehensive economic assessments for integrated approaches. Few studies have conducted detailed cost-benefit analyses comparing IPM packages with conventional pesticide-based systems (Toader et al., 2020). Without clear economic evidence accounting for inputs, labor, equipment, yield gains, environmental benefits, and long-term soil health, growers have little incentive to adopt complex IPM systems. Product availability also presents a barrier, as consistent access to high-quality biological and botanical formulations remains limited for many farmers.

To overcome these obstacles, future research must prioritize rigorous field validation of IPM protocols. This includes developing context-specific treatment schedules, optimizing application techniques, and adapting formulations of biological and botanical agents to enhance stability and field efficacy (Saberi-Riseh et al., 2021; Toshova et al., 2024). There is also a pressing need for user-friendly decision support systems that incorporate real-time pest monitoring data, detailed weather forecasts, and clear economic thresholds to guide farmers in making timely and informed management decisions. Investing in farmer education and robust extension services will be crucial to facilitate the adoption of complex IPM strategies, build confidence in alternative methods, and ensure that scientific advancements translate into practical, sustainable solutions at the farm level. Such comprehensive approaches are essential to achieve the EU's ambitious pesticide reduction targets while safeguarding maize productivity under increasingly challenging pest pressures.

6. CONCLUSIONS

Tanymecus dilaticollis remains a major threat to maize production in Romania and Eastern Europe, particularly following the EU ban on neonicotinoid seed treatments, which eliminated the most effective early-stage control option. This regulatory shift has created an urgent need for viable alternative control measures.

The present review demonstrates that, although no single alternative fully replicates the broad-spectrum efficacy of neonicotinoid seed treatments, several promising options are available. Biological control agents (*Beauveria bassiana*, *Steinernema carpocapsae*, *Bacillus thuringiensis*, *Trichoderma harzianum*), botanical insecticides (neem oil, azadirachtin), and microbial biostimulants offer partial but valuable protection, especially when implemented in combination.

Agroecological practices, including crop rotation and organic amendments, further contribute to pest suppression and strengthen crop resilience. The integration of these diverse tactics within an IPM framework, supported by advanced monitoring tools and decision support systems, currently represents the most sustainable and effective strategy for controlling *T. dilaticollis* in maize systems.

Nevertheless, several limitations continue to hinder widespread adoption. Inconsistent field performance, limited market availability of biological products, and the absence of comprehensive economic data on integrated approaches all present significant challenges. Without clear cost-benefit assessments that consider not only input costs but also yield outcomes, environmental benefits, and long-term soil health, many farmers remain reluctant to transition from conventional pesticide-based programs.

To compensate for the loss of systemic insecticides and ensure reliable, long-term pest management, further efforts are essential. These include continued field validation, refinement of integrated strategies, improved biological formulations, the development of user-friendly monitoring technologies, and targeted farmer training programs.

A coordinated research, policy, and extension effort will be critical to translate existing scientific knowledge into practical, farmer-oriented solutions, thereby achieving both regulatory objectives and sustainable maize production under the evolving European agricultural framework.

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