Review

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Global Advances and Regional Strategies in Maize Pest Management: A Contemporary Review

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Abstract: Maize (*Zea mays*) is a global staple crop that plays a critical role in food security; however, its production is increasingly threatened by insect pests. These challenges have intensified due to globalization, climate change, and agricultural intensification. Invasive species such as *Spodoptera frugiperda* have caused substantial yield losses across Africa and Asia, while native pests including *Ostrinia furnacalis* and *Diabrotica virgifera virgifera* continue to develop resistance to pesticides and Bt maize. Pest profiles differ considerably across regions, resulting in different management programs. The Americas rely heavily on integrated strategies combining *Bacillus thuringiensis* (Bt) maize, crop rotation, and precision pesticide applications; Africa emphasizes low-cost solutions such as climate-adapted push–pull systems and microbial biopesticides; Asia prioritizes policy-driven integrated pest management (IPM) and large-scale releases of *Trichogramma* spp.; Europe focuses on agroecological practices and precision monitoring technologies; and Oceania adopts integrated approaches tailored to irrigated and rainfed production systems. Integrated pest management remains the cornerstone of sustainable maize protection, combining advanced monitoring technologies (e.g., remote sensing and AI-based models), cultural practices (such as intercropping and improved resistant varieties), biological control (including natural enemies and microbial agents), behavioral manipulation (e.g., pheromone traps and push–pull strategies), and regulated chemical control with resistance management. Emerging technologies, including digital agriculture, CRISPR-based breeding, and ecological engineering, offer promising opportunities for future pest management. However, major challenges remain, including insufficient cross-border collaboration, widespread pesticide resistance, unequal access to advanced technologies, and uncertainties in pest dynamics under climate change. Addressing these issues will require coordinated global monitoring networks, equitable technology transfer, promotion of agroecological practices, and standardized resistance management frameworks. Sustainable maize pest management therefore depends on transnational cooperation and innovative, context-specific strategies to safeguard global food security in a changing climate.

Key words: maize pest; global IPM; sustainable agriculture; invasive species; climate resilience

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INTRODUCTION

Maize (*Zea mays*) is a cornerstone of global food security, ranking first among cereal crops in total production and serving as an essential source of food, feed, and industrial raw materials (Erenstein et al., 2022; Liu et al., 2025). It is cultivated across diverse agroecosystems ranging from temperate corn belts to tropical smallholder farming systems, supporting the livelihoods of billions of people worldwide.

Despite its global importance, maize production faces increasing threats from insect pests (Savary et al., 2019). The distribution and severity of these pests have been significantly reshaped by globalization, climate change, and intensified agricultural practices (Bebber et al., 2013; Wang et al., 2022). Among these threats, the transboundary spread of invasive pests—most notably the fall armyworm (*Spodoptera frugiperda*)—has become a major global concern.

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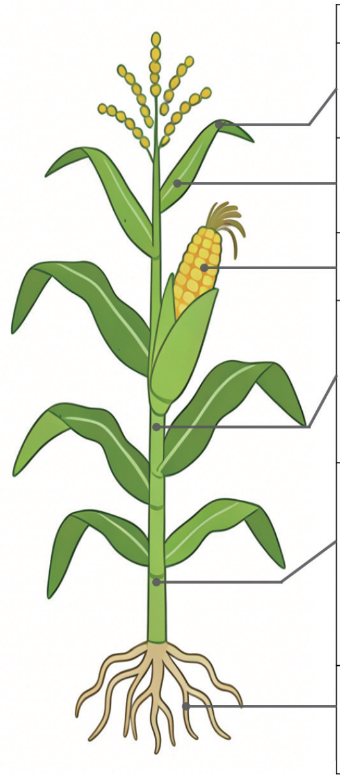
Since its spread beyond the Americas, this pest has caused severe maize yield losses valued at billions of dollars annually in Africa and Asia (Jing et al., 2020; Nyamutukwa et al., 2022; Palli et al., 2023). Climate change further exacerbates pest-related challenges. Rising temperatures accelerate pest metabolism, expand geographical ranges, and increase overwintering survival rates, thereby increasing the frequency and severity of pest outbreaks (Deutsch et al., 2018; Haider et al., 2025). At the same time, agricultural intensification—characterized by monoculture systems and heavy reliance on chemical pesticides—has disrupted natural pest regulation mechanisms, promoted pesticide resistance, and degraded ecosystem services (Desneux et al., 2007; Emery et al., 2021). Under these circumstances, the development of integrated, sustainable, and regionally adapted pest management strategies has become increasingly urgent. This review synthesizes global advances in maize pest management, compares regional pest complexes and control frameworks, highlights emerging technologies and innovations, and identifies key challenges and future research directions. By integrating global perspectives with regional experiences, this review aims to provide a comprehensive reference for researchers, policymakers, and agricultural practitioners working to safeguard maize production and global food security.

Global and Regional Pest Profiles and Management

Maize is cultivated across multiple continents under highly diverse climatic, economic, and technological conditions. As a result, the composition of economically important maize insect pests varies substantially among regions of the world (Savary et al., 2019). Chiang (1978) provided one of the earliest global compilations of maize insect pests of economic importance in Africa, the Americas, Asia, and Europe. Building on this foundation, the present review updates the global inventory of maize insect pests based on recent literature (Fig. 1). Understanding these regional differences is essential for designing pest management strategies that are appropriate to local ecological and socioeconomic contexts (Table 1).

The Americas

The Americas represent the native range of several major maize pests and therefore experience complex pest assemblages. The fall armyworm (*S. frugiperda*) is a highly polyphagous species native to tropical and



Feeding Niche	Africa	Americas	Asia	Europe	Oceania
SUCKING INSECT	*Cicadulina spp.* *Dalbulus spp.* *Dysdercus superstitionus* *Rhopalosiphum maidis* *Peregrinus maidis* *Tetranychus urticae*	*Blissus leucopterus* *Dalbulus spp.* *Frankiniela spp.* *Hercothrips fasciatus* *Peregrinus maidis* *Rhopalosiphum maidis* *Tetranychus urticae*	*Aphis sacchari* *Cicadulina sp.* *Rhopalosiphum maidis* *Peregrinus maidis* *Pyrilla perpusilla* *Tetranychus urticae*	*Cicadida sp.* *Myzus sp.* *Rhopalosiphum maidis* *Tetranychus urticae*	*Rhopalosiphum maidis* *Tetranychus urticae*
FOLIAGE FEEDERS	*Epilachna sp.* *Locusta migratoria* *Schistocerca gregaria* *Spodoptera frugiperda* *Zonocerus variegatus*	*Melanoplus spp.* *Schistocerca paranensis* *Sc. impleta* *Spodoptera frugiperda*	*Locusta migratoria* *Hieroglyphus nigroreplethus* *Monolepta hieroglyphica* *Mythimna separata* *Patanga succincta* *Spodoptera frugiperda* *Sp. exigua*	*Melanogryllus desertus* *Phyllotreta vittula* *Spodoptera frugiperda*	*Chortoicetes terminifera* *Mythimna separata* *Spodoptera frugiperda*
EAR FEEDERS	*Argyroploce leucotreta* *Busseola fusca* *Helicoverpa armigera* *Sesamia spp.* *Spodoptera frugiperda*	*Helicoverpa zea* *Pyroderces sp.* *Protocleucania albilinea* *Pococera atramentalis* *Spodoptera frugiperda*	*Grapholita delineana* *Helicoverpa armigera* *Ostrinia furnacalis* *Os. salientalis* *Spodoptera frugiperda*	*Helicoverpa armigera* *Ostrinia nubilalis* *Pyroderces rileyi* *Sesamia cretica* *Spodoptera frugiperda*	*Helicoverpa armigera* *Spodoptera frugiperda*
STEM BORERS	*Busseola fusca* *Chilo partellus* *Chilotraea argyrolepia* *Coniesta ignefusalis* *Eldana saccharina* *Ostrinia nubilalis* *Sesamia calamistis* *Se. cretica* *Se. nonagrioides* *Se. penniseti* *Se. poephaga* *Spodoptera frugiperda*	*Chilo plejadellus* *Diatraea saccharalis* *Elasmopalpus lignosellus* *Nomophila noctuella* *Ostrinia nubilalis* *Spodoptera frugiperda* *Zediatraea lineolata* *Z. grandiosella*	*Chilo partellus* *Ostrinia furnacalis* *Os. salientalis* *Sesamia inferens* *Spodoptera frugiperda*	*Chilo partellus* *Chi. zonellus* *Diatraea grandiosella* *Di. crambioides* *Ostrinia nubilalis* *Sesamia cretica* *Spodoptera frugiperda*	*Ostrinia furnacalis* *Spodoptera frugiperda*
FEEDERS ON LOWERSTEM AND SEEDLING	*Agrotis ipsilon* *Ag. segetis* *Marasmia spp.* *Spodoptera exempta* *Sp. exigua* *Sp. frugiperda* *Sp. littoralis*	*Agrotis ipsilon* *Chaetocnema spp.* *Dargida grammivora* *Feltia annexa* *Marasmia trapezalis* *Mocis latipes* *Mo. repanda* *Prodenia ornithogalli* *Prod. eridania* *Prod. sunia* *Prod. latifascia* *Prorachia daria* *Pseudaletia unipuncta* *Ps. adultera* *Spodoptera frugiperda*	*Agrotis sp.* *Marasmia trapezalis* *Myllocerus spp.* *Pseudaletia spp.* *Plusia chalceites* *Prodenia litura* *Spodoptera exempta* *Sp. frugiperda* *Tanymecus indicus*	*Agrotis segetum* *Chaetocnema tibialis* *Cha. culicaria* *Elachiptera cornuta* *Geomya tri punctata* *Laphygma exempta* *Loxostege sticticalis* *Lethrus apterus* *Lema melanopa* *Noctuidae* *Oscinella frit* *Os. pusilla* *Tanypezus dilataticollis*	*Agrotis ipsilon* *Spodoptera frugiperda*
ROOT FEEDERS	*Atylus atomaculatus* *Elateridae* *Heteronychus spp.* *Phyllophaga spp.* *Termites*	*Diabrotica spp.* *Dyscinetus sp.* *Euthoela sp.* *Ligyrus sp.* *Phyllophaga spp.*	*Atherigona spp.* *Holotrichia consanguinea* *Leucopholis irrorata* *Microtermes spp.* *Monolepta hieroglyphica* *Odontotermes spp.*	*Agriotes sp.* *Bryoscorpa personata* *Br. gallarum* *Diabrotica spp.* *Elateridae* *Hylemyia platura* *Gryllotalpa gryllotalpa* *Melolontha spp.*	*Costelytra giveni* *Gryllotalpa gryllotalpa* *Melolontha spp.*

Fig. 1. Maize insects of major economic importance and their feeding niches in Africa, the Americas, Asia, Europe and Oceania.

Table 1. Summary table showing key pests and management methods per world region.

Continent	Key Maize Pest Species	Main Management Methods	References
Americas	*Spodoptera frugiperda*	Bt maize (Cry/Vip toxins), refuge strategy, egg parasitoids, push–pull technology	Gassmann & Reisig, 2023
	Diabrotica virgifera virgifera	Soil-applied insecticides, crop rotation, Bt maize with multiple toxins	Gray et al., 2009
	Helicoverpa zea	Bt maize, pheromone trapping	Olmstead et al., 2016; Kwadha et al., 2025
	Ostrinia nubilalis	Bt maize, *Trichogramma*, insecticide sprays	Franeta et al., 2025; Kacar et al., 2023
	Dichelops furcatus	No-till system adjustment, crop rotation, natural enemy conservation	Jacobi et al., 2022
Africa	*Spodoptera frugiperda*	Climate-adapted push–pull, minimum tillage, intercropping	Baudron et al., 2019; Midega et al., 2018
	Busseola fusca	Bt maize (MON810/MON89034)	Tefera et al., 2016; Strydom et al., 2025
	Chilo partellus	Bt maize, landscape-level management, natural enemy conservation	Otim et al., 2022; Kebede et al., 2019
	Sesamia nonagrioides	Bt maize	Kacar et al., 2023
Asia	*Ostrinia furnacalis*	Mass release *Trichogramma*	Iqbal et al., 2021; Wang et al., 2024
	Spodoptera frugiperda	Maize–legume/alfalfa intercropping, Bt maize, microbial biopesticides	Wu et al., 2022; Yang et al., 2024; Chen et al., 2025
	Helicoverpa armigera	Toxicant-infused bait, remote sensing monitoring, insecticide sprays	Sári-Barnácz et al., 2023; Wang et al., 2023a
	Rhopalosiphum maidis	Resistant maize breeding, aphid parasitoids	Wang et al., 2023b
	Monolepta hieroglyphica	Yellow sticky traps, drip irrigation insecticides	Yi et al., 2025; Yan et al., 2023
Europe	*Ostrinia nubilalis*	Bt maize (Cry1Ab), *Trichogramma brassicae*, crop rotation	García et al., 2023; Camerini et al., 2024
	Diabrotica virgifera virgifera	Insecticide sprays, pheromone/digital monitoring, soil granular insecticides	Amarghioalei et al., 2025; Purice & Grozea, 2025
	Sesamia nonagrioides	Bt maize, high-dose/refuge strategy	García et al., 2023
	Chilo partellus	Chemical control, natural enemy utilization, monitoring	Pehlivan & Atakan, 2025; Akmese et al., 2023
Oceania	*Spodoptera frugiperda*	Braconidae and Eulophidae parasitoids release	Fagan-Jeffries et al., 2024
	Helicoverpa armigera	Bt maize (Vip toxins)	Chakroun et al., 2016
	Mythimna separata	Legume-based cover crops, ecological intensification	Trolove et al., 2024
	Diadegma semiclausum	Plant volatile-based attractant	Yazdani & Baker, 2018

subtropical regions of the Americas and is capable of causing significant damage to maize and other crops (Kenis et al., 2023). Another major pest is the western corn rootworm (*Diabrotica virgifera virgifera*), which has developed resistance to both insecticides and *Bacillus thuringiensis* (Bt) maize across the U.S. Corn Belt (Gassmann et al., 2025; Pereira et al., 2022). Additional important pests include the European corn borer (*Ostrinia nubilalis*) and the corn earworm (*Helicoverpa zea*), both of which have evolved resistance to multiple Bt toxins (Tabashnik and Carrière, 2019; Yang et al., 2020). Management strategies in the Americas rely heavily on integrated approaches that combine transgenic Bt maize (e.g., Cry1Ab, Cry2Ab, Vip3Aa20), crop rotation—particularly to control corn rootworm—and targeted chemical control measures (Reay-Jones et al., 2016; Ye et al., 2025). In order to delay the development of insect resistance to the toxins, refuges of non-Bt maize are planted to ensure a pool of susceptible target pests for mating and mingling with any Bt-resistant pests that emerge. The practice of "refuge-in-a-bag" (RIB), in which 5% or 10% non-Bt seed is mixed into a bag of Bt maize, has been widely adopted by seed companies for maize-growing regions in the U.S. (Walsh and Battagliotti, 2025). Brazil implements structured refuge strategies, which consist of a separate block or strip of non-Bt maize (typically 5%–20% of the total area) adjacent to or within a Bt maize field, to delay the evolution of resistance. In addition, the combined management of entomopathogenic fungi resulted in a reduction in *Dalbulus maidis* infestation (Maia et al., 2025; Walsh and Battagliotti, 2025). Biological control also contributes to pest suppression, with augmentative releases of egg parasitoids such as *Trichogramma* spp. and *Telenomus remus* widely applied against lepidopteran pests (Bueno et al., 2023; Kenis et al., 2023).

Africa

Maize pest dynamics in Africa have changed dramatically following the invasion of the fall armyworm in 2016. Since its introduction, the pest has spread to more than 44 countries and is estimated to cause annual yield losses of US$2.5–US$6.3 billion (Midega et al., 2018; Nyamutukwa et al., 2022). Native pests, including the African stem borer (*Busseola fusca*) and the spotted stem borer (*Chilo partellus*), continue to cause substantial damage, with *B. fusca* populations in South Africa having developed resistance to Cry1Ab Bt maize (Strydom et al., 2025; Tefera et al., 2016). Other economically important pests include the sorghum stem borer (*Sesamia calamistis*) and aphids such as *Rhopalosiphum maidis*, which transmit plant viruses (Kebede et al., 2019; Li et al., 2022). Pest management in Africa is constrained by limited financial resources, restricted access to advanced technologies, and the vulnerability of smallholder farming systems (Baudron et al., 2019; Van den Berg et al., 2022). Consequently, many management strategies emphasize affordable and scalable approaches. The climate-adapted push–pull system is among the most successful examples, combining maize intercropped with drought-tolerant *Desmodium* species and border planting of *Brachiaria* grasses to repel pests and attract natural enemies (Alexandridis et al., 2023; Midega et al., 2018). Additional strategies include the application of microbial biopesticides such as *Metarhizium anisopliae* and *Bacillus thuringiensis*, as well as farmer field schools that promote knowledge exchange and IPM adoption (Aravindaram et al., 2026; Nyamutukwa et al., 2022).

Asia

Asia's maize pest complex is dominated by the Asian corn borer (*Ostrinia furnacalis*), which causes annual yield losses of 6–9 million tons in China alone (Zang et al., 2021). The fall armyworm invaded Asia in 2018, becoming a major threat to maize production in China and India (Ganiger et al., 2018; Jing et al., 2020; Song et al., 2025). Other key pests include the oriental armyworm (*Mythimna separata*), the maize borer (*Conogethes punctiferalis*, *C. partellus*), and aphids (*R. maidis*, *Aphis gossypii*) (Dong et al., 2023; Li et al., 2022; Wang et al., 2023a). Management strategies in Asia are characterized by policy-led IPM campaigns, large-scale biological control, and technological innovation. China has promoted the mass release of *Trichogramma* spp. (e.g., *Tr. dendrolimi*, *Tr. ostriniae*) for controlling the Asian corn borer, covering nearly 4 million hectares annually (Zang et al., 2021; Wang et al., 2024). *Trichogramma chilonis* can be released against corn stem borer, *C. partellus* in India (Shera et al., 2017). Pheromone traps and intelligent monitoring systems (e.g., improved YOLO models for pest detection) are widely used for surveillance (Deng et al., 2023; Lv et al., 2022). Additionally, transgenic Bt maize (e.g., MON810, Cry1Ab+Cry2Ab+Cry1Fa) is being evaluated and deployed to control lepidopteran pests, with strict resistance monitoring in place (Suby et al., 2020; Chen et al., 2025; Li et al., 2020).

Europe

In Europe, maize pest communities are primarily dominated by the European corn borer and the western corn rootworm, the latter of which was introduced from North America and has become an invasive pest in several countries (García et al., 2023; Pereira et al., 2022). Aphid species such as *Rhopalosiphum padi* and *Sitobion avenae* are also important pests due to their role in transmitting barley yellow dwarf viruses (Gilabert et al., 2017). In addition, the spotted stem borer (*C. partellus*) has recently invaded Turkey and expanded its distribution to multiple provinces (Akmese et al., 2023; Pehlivan and Atakan, 2025). Bt maize producing Cry1Ab has been cultivated in Spain and Portugal since 1998, with resistance management based on the high-dose/refuge strategy and systematic monitoring programs (García et al., 2023). Furthermore, crop rotation and habitat management practices—including flower strips and hedgerows—are promoted to enhance natural enemy populations and support biological pest control (Camerini et al., 2024; Yousefi et al., 2024). Precision monitoring technologies, such as pheromone traps and automated digital monitoring systems, are increasingly used to track pest populations and guide management decisions (Kwadha et al., 2025; Purice and Grozea, 2025).

Oceania

The maize pest complex in Oceania includes the corn earworm (*Helicoverpa armigera*), and cosmopolitan armyworm (*M. separata*) (Bird et al., 2023; Trolove et al., 2024). More recently, the fall armyworm has invaded Australia, further increasing pest pressure in the region (Kenis et al., 2023). Management strategies in Oceania emphasize integrated approaches adapted to both irrigated and rainfed production systems, with a strong focus on biological control and reduced reliance on chemical pesticides. Conservation of natural enemies—such as Hymenopteran parasitoids—plays an important role in suppressing pest populations (Fagan-Jeffrie et al., 2024). Microbial biopesticides and precision pesticide applications are also widely adopted (Van den Berg and du Plessis, 2022; Vivekanandhan et al., 2023). Pest monitoring systems primarily rely on pheromone traps and regular field scouting to detect infestations at an early stage (Sisay et al., 2024). In New Zealand, the use of legume-based cover crops has been shown to suppress weeds, reduce pest damage, and improve maize yields while lowering armyworm populations (Trolove et al., 2024).

Integrated Pest Management on Maize

Integrated pest management represents a holistic approach that combines multiple tactics for sustainable pest control. The following sections examine key IPM components and their implementation across global maize production systems (Fig. 2).

Monitoring and forecasting: global technological advancement

Commercialized monitoring and forecasting tools for maize insect pests have advanced significantly, integrating remote sensing and automated trapping systems. Satellite-based platforms such as Sentinel-2 and Landsat 8 are now routinely used for large-scale surveillance of crop health and pest damage, with spectral bands in visible and shortwave infrared regions effectively detecting maize ear damage caused by *H. armigera* (Lv et al., 2022; Sári-Barnácz et al., 2023). Unmanned aerial vehicles (UAVs) equipped with multispectral sensors provide high-resolution imagery for real-time field monitoring, enabling early detection of pest infestations and precise assessment of crop health (Martin and Latheef, 2019; Yan et al., 2025).

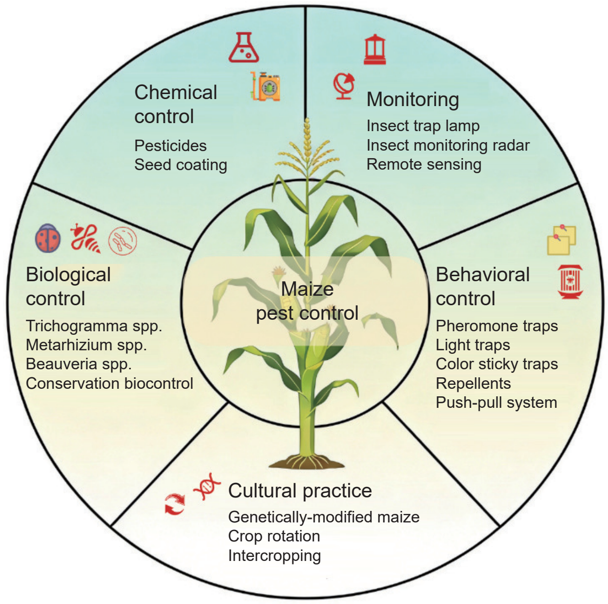


Fig. 2. Practices in integrated pest management programs for maize.

Pheromone-based trapping remains a widely adopted commercial method. Sex pheromone lures and traps are routinely used to monitor population dynamics of *H. armigera*, *O. furnacalis*, and *S. frugiperda* in maize fields (Kim et al., 2018; Sisay et al., 2024). Food attractant-based traps have also been commercialized for *S. frugiperda*, providing comparable performance to sex pheromones and enabling the capture of both sexes, which improves forecasting of fecundity and migration (He et al., 2023). These commercialized technologies collectively enable data-driven, proactive pest management in maize production systems worldwide.

Cultural practices: global practices and adaptation

Cultural practices constitute an essential component of integrated pest management, aiming to reduce pest pressure through crop management strategies, genetic improvement and diversified cropping systems.

Among genetic control approaches, transgenic Bt maize remains the most widely adopted technology for controlling lepidopteran pests. Pyramided Bt traits, such as Cry1Ab+Cry2Ab+Cry1Fa, provide broad-spectrum protection against multiple insect species and have been widely implemented in several maize-producing regions (Chen et al., 2025; Yang et al., 2024). However, the evolution of pest resistance poses a growing challenge, with species such as *Busseola fusca* and *S. frugiperda* developing resistance to both single and stacked Bt toxins (Strydom et al., 2025; Van den Berg and du Plessis, 2022). In the United States, resistance management for Bt maize includes refuge strategies designed to maintain susceptible pest populations and delay resistance evolution. Similarly, in China, refuge systems involving Bt maize combined with non-Bt cotton have been used to delay resistance development in pests such as the pink bollworm (Gassmann and Reisig, 2023; Tabashnik and Carrière, 2019).

In addition to genetic approaches, crop diversification strategies play a key role in cultural pest management. Intercropping systems, particularly those involving legumes such as cowpea, pigeon pea, or alfalfa, can reduce pest infestations by disrupting pest host-finding behavior and enhancing populations of natural enemies (Soujanya et al., 2024; Wu et al., 2022). Crop rotation remains another important strategy, especially maize–soybean rotations used to suppress western corn rootworm populations. However, behavioral adaptations in some pest species have reduced the effectiveness of rotation in certain regions (Gray et al., 2009; Jacobi et al., 2022).

Overall, cultural practices contribute to pest suppression while simultaneously improving agroecosystem resilience and sustainability.

Biological control: international experience and innovation

Biological control represents a cornerstone of sustainable maize pest management, relying on natural enemies, microbial insecticides, and conservation strategies to suppress pest populations while minimizing environmental impacts. These approaches have been widely adopted across maize-producing regions as essential components of integrated pest management programs.

Egg parasitoids of the genus *Trichogramma* are among the most extensively used biological control agents worldwide. Large-scale releases of these parasitoids have been implemented in several countries, including China, India, and Myanmar, to control key lepidopteran pests such as the Asian corn borer and the fall armyworm (Dai et al., 2026; Myint et al., 2023; Zang et al., 2021). Among them, *Trichogramma dendrolimi* demonstrates enhanced and prolonged parasitism of Asian corn borer eggs when released at different developmental stages. In contrast, the parasitism efficiency of *Trichogramma ostriniae* appears less sensitive to release timing and can be significantly enhanced when the parasitoids are reared on the factitious host *Antheraea pernyi*, which improves their fitness and parasitism capacity (Iqbal et al., 2021; Li et al., 2024; Zang et al., 2021). In addition to *Trichogramma* species, other parasitoids and predators contribute significantly to maize pest suppression. For example, parasitoids such as *T. remus* and predators including *Chrysoperla carnea* are frequently used to manage lepidopteran pests in maize fields (Bueno et al., 2024; Huang et al., 2026; Franeta et al., 2025). These natural enemies play an important role in regulating pest populations, particularly when integrated with other IPM practices.

Microbial biopesticides have also gained increasing attention as environmentally friendly alternatives to chemical insecticides. Entomopathogenic fungi such as *Beauveria bassiana* and *M. anisopliae*, bacterial agents such as *B. thuringiensis*, and viral agents including nuclear polyhedrosis virus have demonstrated effectiveness against a range of maize pests. Recent innovations have further enhanced the performance of microbial agents. For example, the integration of *B. bassiana* with graphene oxide (GO-Bb nanocomposites) improves its thermal stability and ultraviolet tolerance, thereby enhancing its effectiveness against the Asian corn borer while simultaneously promoting maize seedling growth (Feng et al., 2023; Zhan et al., 2026). Similarly, *M. anisopliae* has shown high pathogenicity against fall armyworm larvae while posing minimal risks to non-target organisms such as earthworms (Aravindaram et al., 2026; Vivekanandhan et al., 2023).

Conservation biological control further strengthens pest regulation by enhancing habitats that support natural enemy populations. Habitat manipulation strategies—such as the establishment of flower strips, hedgerows, and field margins—can significantly increase the abundance and diversity of predators and parasitoids in maize fields (Gurr et al., 2017; Wang et al., 2025a; Wang et al., 2026). Agri-environmental practices that increase habitat complexity have been shown to improve pest suppression. For instance, in Ethiopia, maize fields bordered by complex hedgerows and enset (*Ensete ventricosum*) fields support higher predator abundance than fields adjacent to simpler hedgerows or khat plantations (Kebede et al., 2018). Similarly, in China, herbaceous strips significantly increased insect biodiversity—particularly populations of parasitic wasps and Staphylinidae—both within the strips and in adjacent maize fields. These ecological infrastructures effectively suppressed herbivorous insect populations and resulted in a maize yield increase of approximately 14.5% ± 2.3% compared with control fields (Yan et al., 2026).

Collectively, these international experiences demonstrate that biological control—through augmentative releases, microbial agents, and habitat management—plays a critical role in sustainable maize pest management. Continued innovation in biological control technologies and ecological approaches will further enhance their effectiveness and integration within global IPM programs.

Behavioral control: technological diffusion

Behavioral control strategies exploit the behavioral responses of pests to environmental cues in order to reduce infestation and crop damage. These methods are increasingly integrated into modern pest management programs due to their ecological compatibility and compatibility with other IPM strategies.

Intelligent trapping technologies—including light traps, pheromone traps, and color sticky traps—are widely used for both pest monitoring and mass trapping. Advanced light traps equipped with sensors and neural network algorithms can selectively capture nocturnal pests such as moths while minimizing non-target insect capture (Hinojosa-Dávalos et al., 2025; Yi et al., 2025). Pheromone traps are also highly effective for monitoring pest populations and guiding management decisions. For example, a ternary blend of (Z)-12-tetradecenyl acetate, (E)-12-tetradecenyl acetate, and n-tetradecyl acetate has been identified as the most effective attractant for male Asian corn borers in Xinjiang, China (Deng et al., 2023; Sisay et al., 2024).

Color sticky traps provide another efficient monitoring tool. Yellow traps corresponding to wavelengths around 580 nm have been shown to effectively capture pests such as *Monolepta hieroglyphica*, particularly when placed near field edges at heights approximately 40 cm above the maize ear level (Yi et al., 2025; Ziaie-Juybari et al., 2021).

Additional behavioral and physical control methods are also emerging. Ultrasonic repellents are being explored in pilot applications in Europe, while drip irrigation systems delivering insecticides such as dimethoate or thiamethoxam enable targeted control of soil-dwelling pests with reduced environmental exposure (Yan et al., 2023; Zheng et al., 2020). Plant volatile-mediated strategies have also gained increasing attention. The push–pull system, originally developed in Africa, exploits pest responses to plant-derived volatiles to repel pests from maize while attracting them to trap crops. This system has demonstrated remarkable effectiveness, reducing fall armyworm damage by up to 82.7% and increasing maize yields by approximately 2.7 times (Luttermoser et al., 2023; Midega et al., 2018; Mobarak et al., 2025).

Recent innovations further expand behavioral control technologies. For instance, UV-protective, water-resistant, and biodegradable micro/nanofiber mats have been developed to enable controlled release of repellents, providing sustained management of pests such as *Holotrichia oblita* (Li et al., 2026).

Chemical control: resistance management

Despite increasing emphasis on ecological approaches, chemical control remains an important component of integrated pest management in maize production systems. However, its use is increasingly guided by standardized practices aimed at reducing environmental impacts and slowing the development of pest resistance. Diamides (e.g., chlorantraniliprole) are the most popular and core pesticides in maize pest control, and the characteristic application is the combination of neem oil and pyrethroids (Gray et al., 2009; Ye et al., 2025). These practices are concise and in line with regional planting characteristics and regulatory requirements.

Advances in precision agriculture technologies have improved the efficiency and accuracy of pesticide applications. Tools such as unmanned aerial vehicles (UAVs) and electrostatic spray nozzles enable targeted pesticide delivery, improving coverage while reducing spray drift and chemical waste (Martin and Latheef, 2019; Yan et al., 2025). Seed treatments with neonicotinoid insecticides, including imidacloprid, are widely used to control early-season pests, although their effectiveness varies depending on pest species and environmental conditions (Douglas and Tooker, 2015; Zhang et al., 2023).

Managing insecticide resistance has become a major global priority. Effective resistance management strategies typically involve rotating insecticides with different modes of action, using synergists, and integrating chemical control with biological and cultural methods. International monitoring programs also play an important role in resistance management. Global databases and surveillance networks track resistance evolution in pest populations, while standardized bioassays are used to assess pest susceptibility to insecticides and Bt toxins (Li et al., 2020; Strydom et al., 2019). These coordinated efforts support the development of evidence-based resistance management strategies and contribute to the long-term sustainability of pest control programs.

Emerging Technologies and Innovations

Digital and precision agriculture

Recent innovations leverage remote sensing, unmanned aerial vehicles (UAVs), artificial intelligence (AI), and IoT-based monitoring to enable real-time, data-driven pest management.

Remote sensing technologies, drones, and artificial intelligence (AI)-driven analytical models now play increasingly important roles in maize pest monitoring systems. Unmanned aerial vehicles (UAVs) equipped with multispectral sensors provide high-resolution real-time imagery for early detection of pest infestations and improved crop health assessment (Martin and Latheef, 2019; Yan et al., 2025).

AI and machine learning have further enhanced pest detection capabilities: deep-learning models such as Maize-YOLO and improved YOLOv3 algorithms can automatically identify maize pests from field images with high accuracy, achieving mean average precision (mAP) exceeding 76% (Wang et al., 2025b; Yang et al., 2023).

Neural-network-guided smart traps with light and rain sensors can selectively capture nocturnal pests while minimizing non-target catches (Hinojosa-Dávalos et al., 2025). Automated digital monitoring systems (e.g., iScout®) provide continuous temporal data on adult activity, complementing traditional traps (Purice & Grozea, 2025). Food attractants have been validated for monitoring *S. frugiperda* seasonal abundance, enabling better forecasting (He et al., 2023).

Beyond detection, predictive modeling plays a crucial role. Ecological niche models like MaxEnt and CLIMEX are widely used to predict pest distribution and potential spread under current and future climate scenarios (Li et al., 2022; Wu et al., 2018). IoT-integrated monitoring platforms incorporate sensors for temperature, humidity, and pest activity, delivering real-time data to farmers via mobile applications (He et al., 2023; Yan et al., 2025). Decision support tools—including dynamic Bayesian network models and other machine learning approaches—synthesize monitoring data, climatic datasets, and pest biological traits to forecast outbreaks and inform control decisions (Bebber et al., 2019; Cros et al., 2021; Haider et al., 2025). Finally, precision application technologies such as UAVs fitted with electrostatic nozzles and variable rate technology (VRT) facilitate site-specific pesticide delivery, minimizing waste and environmental footprint (Martin and Latheef, 2019; Yan et al., 2025).

Biotechnology and genomics

Biotechnology and genomics are accelerating the development of pest-resistant maize germplasm. Multiplex genome editing of whole gene families (e.g., BREEDIT pipeline) improves complex traits such as leaf architecture and yield in maize (Lorenzo et al., 2023). CRISPR/Cas9-mediated mutations in cadherin, ABCC2, and ABCC3 revealed functional redundancy in Bt toxin pathways against *O. furnacalis*, providing insights for resistance management (Wang et al., 2025c). The technology is also used to create smart-canopy architecture (e.g., lac1 mutant) for high-density planting (Tian et al., 2024). Recent reviews highlight CRISPR's potential for enhancing biotic and abiotic stress tolerance (Chen et al., 2024; Li et al., 2025).

New pyramided Bt events (e.g., Cry1Ab+Cry2Ab+Cry1Fa) show high efficacy against multiple lepidopteran pests, including *S. frugiperda*, *H. armigera,* and *O. furnacalis* (Chen et al., 2025). However, resistance evolution remains a concern, with sequential resistance documented in western corn rootworm (Gassmann et al., 2025) and *B. fusca* (Strydom et al., 2025). Blended refuge strategies and structured refuges are being refined for smallholder systems (Kang et al., 2025).

QTL mapping and multi-omics profiling identified candidate genes (e.g., Zm00001d035736) for corn leaf aphid resistance, involving flavonoid biosynthesis and jasmonic acid pathways (Wang et al., 2023b). Physical defense mechanisms against spider mites were linked to stomatal traits (Di et al., 2024).

Although not yet extensively documented in the reviewed field studies, RNAi-based biopesticides (e.g., spray-induced gene silencing) represent a promising next-generation strategy for species-specific pest control. Future research should focus on developing stable dsRNA formulations and assessing their field efficacy against key maize pests such as *O. furnacalis* and *S. frugiperda*.

Ecological engineering

Ecological engineering centers on the design of agroecosystems to strengthen natural pest regulation and reduce dependence on synthetic inputs. Habitat manipulation strategies—including intercropping, cover cropping, and flower strip establishment—enhance agroecosystem biodiversity and furnish resources for natural enemies (Kebede et al., 2018; Yousefi et al., 2024). Maize–alfalfa intercropping reduces fall armyworm incidence by 80% and improves the land equivalent ratio, whereas legume cover crops suppress weeds and mitigate pest injury (Trolove et al., 2024; Wu et al., 2022). Landscape-level management practices—such as reducing monocropping and augmenting habitat heterogeneity—boost the biocontrol services provided by beneficial arthropods. In France, landscape grassland cover reduces aphid colonization of maize; in Ethiopia, smaller field dimensions and greater field border density correlate with higher predator abundance (Gilabert et al., 2017; Kebede et al., 2019). The push-pull cropping system, a flagship ecological engineering approach, employs plant semiochemicals to repel pests and recruit natural enemies, delivering sustainable pest suppression across sub-Saharan Africa and Asia (Erdei et al., 2024; Midega et al., 2018).

Climate-smart pest management

Climate-smart pest management seeks to adapt to and mitigate climate-driven shifts in pest population dynamics. Predictive modeling leveraging climatic datasets and species distribution models (SDMs) forecasts shifts in pest geographic ranges and outbreak risk, guiding adaptive management (Li et al., 2022; Wu et al., 2018). Resilient cropping systems—such as drought-tolerant maize intercropped with drought-resistant legumes—reduce crop vulnerability to climate extremes and associated pest pressure (Alexandridis et al., 2023; Zanzana et al., 2025). Adaptive tactics include adjusting sowing dates to evade peak pest pressure, modifying irrigation regimes to disrupt pest habitats, and deploying pest-resistant cultivars adapted to altered climatic conditions (Haider et al., 2025; Rezaei et al., 2023). Climate-smart IPM merges these practices with biological, physical, and chemical control to build agroecosystem resilience. For instance, in the United States, climate change projections identify regions at elevated risk of aflatoxin contamination, directing targeted monitoring and mitigation (Wang et al., 2022; Yu et al., 2022).

Nanotechnology and advanced delivery systems

Nanomaterials are emerging as tools to enhance the efficacy of biocontrol agents and reduce pesticide use. Graphene oxide (GO) as a nanocarrier for *B. bassiana* (GO-Bb nanocomposite) improved spore thermal stability and UV resilience. Field experiments showed that GO-Bb reduced *O. furnacalis* damage, activated phytohormone signaling, and up-regulated benzoxazinoid (BX) defense genes, offering dual benefits for pest control and plant growth (Zhan et al., 2026).

A methacrylic-anhydride-functionalized cellulose nanocrystal-stabilized high internal phase Pickering emulsion (MCNCs-HIPPE) was developed for imidacloprid delivery. The formulation exhibited cellulase-promoted and temperature-dependent release, improved leaf adhesion, rain resistance, and lower LC_{50} against *R. maidis* compared to a commercial emulsifiable concentrate, with reduced environmental risk (Zhou et al., 2026). Combining RNAi with nanocarriers (e.g., layered double hydroxide or chitosan nanoparticles) could enable efficient delivery of dsRNA into pest insects. Although not yet reported in the current literature set for maize pests, such platforms hold great promise for sequence-specific, environmentally benign pest control.

Challenges and Barriers to Implementation

Inadequate cross-border collaboration and information sharing

Fragmented cross-national pest monitoring networks delay early warning of invasive pests such as the fall armyworm, which spreads rapidly across national boundaries (Bebber et al., 2019; Guo et al., 2024;

Song et al., 2025). Divergent phytosanitary regulations and data-sharing protocols impede coordinated transboundary pest suppression, resulting in inconsistent management and recurrent invasions (Kenis et al., 2023; Muniappan et al., 2024). Limited pest identification and monitoring capacity in low- and middle-income countries exacerbates this gap, with numerous pests remaining unreported or misdiagnosed (Bebber et al., 2019; Nyamutukwa et al., 2022).

Widespread pesticide resistance and environmental risks

Pesticide resistance constitutes a global crisis, with *S. frugiperda* evolving resistance to multiple insecticide classes in more than 40 countries (Strydom et al., 2025; Van den Berg and du Plessis, 2022). Bt resistance is similarly pervasive: *B. fusca* exhibits resistance to Cry1Ab Bt maize in South Africa, and *H. zea* is resistant to Cry1 and Cry2 toxins in the United States (Gassmann et al., 2025; Tabashnik and Carrière, 2019). Overreliance on pesticides drives environmental contamination; neonicotinoid exposure impairs pollinators and other non-target organisms across Europe and North America (Desneux et al., 2007; Douglas and Tooker, 2015).

Uneven access to advanced technologies

A pronounced technology adoption gap persists between developed and developing nations. Transgenic Bt maize and intelligent monitoring equipment are widely deployed in the United States and Europe, yet high costs and limited availability restrict uptake by smallholder farmers in Africa and Asia (Baudron et al., 2019; Van den Berg et al., 2022). Policy constraints—including restrictions on genetically modified (GM) crops in parts of Europe—further limit technological access (García et al., 2023; Yousefi et al., 2024). This digital and biotechnological divide widens global food security disparities, leaving developing regions disproportionately vulnerable to pest outbreaks.

Uncertainty of pest dynamics under climate change

Climate change is reshaping pest distribution, phenology, and population dynamics, complicating outbreak prediction and effective control strategy design (Bebber et al., 2013; Wang et al., 2022). Elevated temperatures accelerate pest metabolism and reproductive rates, increasing outbreak frequency and severity; altered precipitation regimes modify pest habitats and natural enemy communities (Deutsch et al., 2018; Haider et al., 2025). Erratic climatic events—including extreme droughts and floods—disrupt pest management operations and reduce the efficacy of cultural and chemical tactics (Hou et al., 2024; Rezaei et al., 2023).

CONCLUSION

Effective maize pest management represents a multifaceted global challenge requiring integrated, adaptive, and geographically tailored strategies. The rapid range expansion of invasive pests, intensifying climate change impacts, and agricultural intensification have collectively restructured pest dynamics across major maize-producing regions. Concurrently, persistent constraints—including insufficient cross-border coordination, widespread pesticide and Bt resistance, and inequitable access to innovative technologies—continue to limit the efficacy and sustainability of pest management practices. Regional pest complexes and management frameworks vary substantially due to differences in agroecological conditions, technical capacity, and policy environments. Nonetheless, several unifying principles have emerged globally. IPM—integrating monitoring technologies, cultural practices, biological control, behavioral manipulation, and judicious chemical use—remains the gold-standard framework for sustainable maize pest control. Continued refinement of resistance management protocols, particularly for Bt crops and synthetic pesticides, is critical to preserving long-term control efficacy.

Emerging technologies—including AI-driven pest surveillance, digital and precision agriculture tools, CRISPR-based crop improvement, and ecological engineering—offer transformative potential to boost pest management efficiency and sustainability. However, successful scaling of these innovations depends on enabling policy environments, effective technology transfer, and equitable farmer access, especially in developing regions where maize is a cornerstone of food security. Future research and policy priorities should prioritize the establishment of global pest monitoring and early-warning networks, strengthened international cooperation in pest surveillance and management, and the promotion of agroecological practices that enhance ecosystem resilience. Additionally, standardized resistance management frameworks and accelerated development of eco-friendly pest control technologies are indispensable to mitigating long-term risks associated with pest adaptation and environmental degradation. Ultimately, sustainable maize pest management demands coordinated global action that integrates scientific innovation, regional empirical knowledge, and inclusive agricultural policies. By fostering international collaboration and developing context-responsive pest management strategies, we can safeguard maize production, minimize environmental harm, and strengthen global food security amid ongoing climatic and ecological change.

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The authors have no conflicts of interest relevant to this article.

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