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Global distribution and sustainable management of Asian corn borer (ACB), *Ostrinia furnacalis* (Lepidoptera: Crambidae): recent advancement and future prospects

Review Article

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Abstract

The Asian corn borer (ACB), *Ostrinia furnacalis* (Guenée, 1854), is a serious pest of several crops, particularly a destructive pest of maize and other cereals throughout most of Asia, including China, the Philippines, Indonesia, Malaysia, Thailand, Sri Lanka, India, Bangladesh, Japan, Korea, Vietnam, Laos, Myanmar, Afghanistan, Pakistan and Cambodia. It has long been known as a pest in South-east Asia and has invaded other parts of Asia, Solomon Islands, parts of Africa and certain regions of Australia and Russia. Consequently, worldwide efforts have been increased to ensure new control strategies for *O. furnacalis* management. In this article, we provide a comprehensive review of the ACB covering its (i) distribution (geographic range and seasonal variations), (ii) morphology and ecology (taxonomy, life-history, host plants and economic importance) and (iii) management strategies (which include agroecological approaches, mating disruption, integrated genetic approaches, chemical as well as biological control). Furthermore, we conclude this review with recommendations to provide some suggestions for improving eco-friendly pest management strategies to enhance the sustainable management of ACB in infested areas.

Introduction

The Asian corn borer (ACB), *Ostrinia furnacalis* (Guenée, 1854) (Lepidoptera: Crambidea) is a polyphagous lepidopteran pest and is the most destructive pest of maize crop throughout Asia, including China (Chen *et al*., 2013, 2015; Li *et al*., 2024*a*). The incidence of maize borer infestation has increased in China due to the substantial growth of crop planting (covering over 20 million hectares of agricultural land), especially maize (Wang and Wang, 2019; Liu *et al*., 2023*a*). In China, pests affect maize production by 10–30% annually (Myint *et al*., 2023). The larvae of *O. furnacalis* feed on all parts of the corn plant at all stages of its growth (Nafus and Schreiner, 1987, 1991), causing serious economic damage to other key food and fibre crops such as sorghum, millet and cotton (Chen *et al*., 2016).

ACB is distributed throughout Asia and has also invaded the Solomon Islands, parts of Africa and certain regions of Australia (Mutuura and Munroe, 1970; Nafus and Schreiner, 1991; Boo and Park, 1998; Grahame, 2022). ACB overwinters as diapausing larvae and exhibits freeze tolerance, particularly in cold areas (Xie *et al*., 2015). In China, ACB shows variable generational patterns depending on geographical latitude and altitude, ranging from one to seven generations each year, with higher latitudes having fewer generations (Shen *et al*., 2020). With the widespread cultivation of maize in Asia, especially in the Northeastern part, the ACB has become highly adapted to this host plant (Kojima *et al*., 2010; Shen *et al*., 2020). It has the ability for long-distance migration and poses a significant threat to new habitats and crop plant economic viability (Shen *et al.*, 2020). Hence, the present article provides an updated review on ACB to compile the global sustainable management alternatives for ACB control, including its (i) distribution (geographic range and seasonal variations), (ii) morphology and ecology (taxonomy, life cycle, host plant range and economic importance) and (iii) management techniques. The management section covers sustainable agricultural practices, mating disruption (MD), resistant cultivars, biological control, biopesticides and chemical control. Finally, we concluded this review with recommendations aimed at improving the sustainable management of ACB in newly infested areas, which may also be valuable for managing other serious crop pests.

Distribution of ACB

ACB is mainly distributed in Asia, which includes China, the Philippines, Thailand, Sri Lanka, India, Korea, Guam, Papua New Guinea, Vietnam, Brunei, Singapore, Laos, Bangladesh, Pakistan, Afghanistan, Cambodia, Indonesia, Myanmar, Malaysia and Japan as illustrated in fig. 1, based on the data collected from CABI and GBIF (GBIF, 2022; Grahame, 2022). Additionally, the Solomon Islands, Northern Mariana Island, parts of Africa and certain regions of Australia and Russia also host a limited population of ACB (Grahame, 2022; Li *et al.*, 2024*a*). ACB thrives in tropical regions due to sustained agricultural practices focused on its preferred host crop year-round. Globally, it is currently reported from 26 countries (Grahame, 2022).

According to a study by Wu *et al.* (2018), the native range of ACB overlaps with major corn production areas in North-eastern, Eastern and South-eastern parts of China, Japan and South-western coastal regions, as presented in fig. 1. The predicted range of maize closely matches that of its herbivore, *O. furnacalis*, with some variations in Northern China and Japan. Li *et al.* (2024*a*) and Wu *et al.* (2018) also found that MaxEnt performed well in predicting the species distribution, with temperature during the Wettest quarter being the most influential variable. The CLIMEX model predicted suitable areas for *O. furnacalis* in Jiangsu and Yunnan, though it tended to be overconservative in Yunnan Province. MaxEnt results indicated a correlation between species distribution and temperature, with preferences for areas with high summer precipitation and precipitation seasonality within moderate isothermal regions.

Insects, as essential arthropods, greatly influence an ecosystem (Ullah *et al.*, 2024*b*). Temperature plays a crucial role in determining the insect and host plants interactions across the globe. Differences in thermal requirements impact the variations between host and pest distributions. ACB has a much lower developmental temperature threshold than its host and shows broader thermal requirements for development across different geographical variations (Quan *et al.*, 2023). Under future climate change scenarios, this suggests a reasonable potential for biological control, but also presents challenges due to variations in life-history traits within ACB populations and the occurrence of multiple generations per year, which could facilitate rapid adaptation to novel environments (Nafus and Schreiner, 1991; Franklin, 2010; Lozier and Mills, 2011; Wang *et al.*, 2014; Xiao *et al.*, 2016; Fu *et al.*, 2022; Li *et al.*, 2024*a*).

In conclusion, ACB's distribution spans Asia, Southeast Asia and beyond, with a notable preference for tropical regions. Understanding its native range and environmental factors affecting its distribution is crucial for pest management and agricultural practices. Although drastic climate variations can impact both host organisms and biocontrol agents, there are still potential opportunities for using biocontrol in an era of climate change. Therefore, the adaptability and diverse traits within species population underscore the need for continuous research and monitoring to mitigate future agricultural impacts.

Geographic range and seasonal variations in distribution

The developmental pathways of ACB across its geographical range exhibit significant variation. This diversity is crucial for comprehending life-history evolution, as emphasised by Nylin (2001). ACB displays evolutionary intra-population differences in voltinism, ranging from one to seven generations annually across different regions of corn cultivation in China (Liu *et al.*, 2023*b*). While commonly considered a facultative larval diapause insect, ACB's development varies under different photoperiods, resulting in distinct voltine ecotypes (Li *et al.*, 1992). Notably, geographical populations showed variations in voltinism, generation rhythm and host plants, reflecting evolutionary adaptations (Liu *et al.*, 2023*b*). Both univoltine and bi-/multivoltine ecotypes in ACB exhibit sigmoidal photoperiod-diapause responses, with differences in critical day length and photoperiodic sensitivity (Liu *et al.*, 2023*b*). Similarly, European corn borer (ECB) ecotypes display differential responses to photoperiods (Showers *et al.*, 1975; Ikten *et al.*, 2011). Field studies reveal sympatric populations with mixed voltinism, indicating natural variation (Jin and Zhang, 1983; Xie *et al.*, 2015). Latitudinal variations significantly impact ACB's life-history traits, including developmental time, body weight and growth rate (Fu *et al.*, 2022). High-latitudinal populations exhibit shorter developmental times, higher body weights and faster growth in non-diapausing pathways, while diapausing pathways show the opposite pattern. Diapause incurs a metabolic cost, especially for males. ACB's body weight is larger in females, influencing sexual size dimorphism. Diapause duration correlates with winter climatic conditions and is genetically influenced. Climate warming may drive multivoltine biotypes and sympatric populations towards increased voltinism (Liu *et al.*, 2023*b*). The differences in diapause duration among ACB populations may have genetic underpinnings, warranting future research. Additionally, ACB's potential spread is influenced by wind patterns and trade contamination, facilitating dissemination once established. In conclusion, the developmental pathways and life-history traits of ACB exhibit intricate adaptations across its geographical range. Understanding these variations sheds light on the evolution and ecological dynamics of this important insect species.

Morphology and ecology

Taxonomy and morphology

Ostrinia Hübner, 1825 is a genus of moths in the family Crambidae (Insecta: Lepidoptera) with 23 described species and 35 subspecies worldwide (Yang *et al.*, 2021). This genus includes several agricultural pests, such as *O. furnacalis*, *O. nubilalis* (ECB) and *O. scapulalis* (Adzuki bean borer). Among these, *O. furnacalis* is one of the most destructive pests of maize. As a result, the morphology and taxonomy of *O. furnacalis* is briefly discussed herein. Based on recent phylogenomics and extensive morphology examinations, the genus *Ostrinia* has been divided into three

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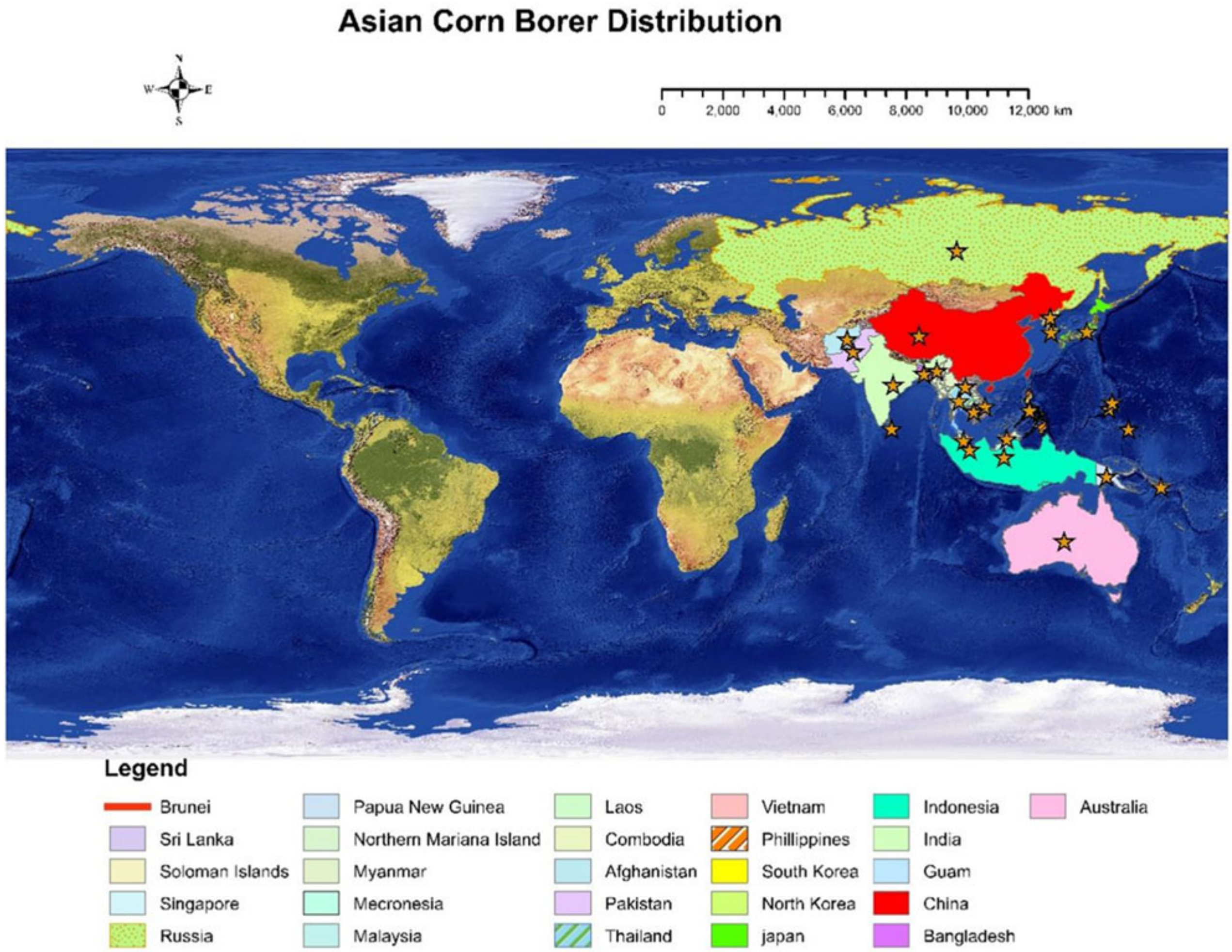

Figure 1. Map showing the global distribution of ACB. The potential distribution herein based on available information from CABI website and GBIF (Global Biodiversity Information Facility). Occurrence points were obtained through the compilation of data from secondary literature sources and the GBIF website, which serves as a comprehensive repository of biodiversity records. The map was prepared by using ArcGIS 10.8.2 software. The occurrence points were geographically mapped onto the Natural Earth Layer, and subsequently (Figure Map), the coloration of the countries where the ACB was observed underwent corresponding alterations.

groups representing clade I (*O. obumbratalis* species group), clade II (*O. penitalis* species group) and clade III (*O. nubilalis* species group) (Han *et al.*, 2020). Among these groups, the third species group contributes 61.1% of all *Ostrinia* species. This species group can be recognised by the male genitalia with two cornuti in the phallus and a V-shaped juxta with both anterior and posterior arms (Yang *et al.*, 2021). Traditionally, this species group is further subdivided into two subgroups based on morphology of male mid-tibia: the small tibia and large tibia, however, this classification has not been supported in recent phylogenomic studies by Yang *et al.* (2021). *Ostrinia furnacalis* is included in the subgroup which comprises male genitalia with trilobed uncus and the small tibia (Kim *et al.*, 1999).

Life cycle and development

The ACB undergoes a well-defined life cycle, crucial for effective management (Rahayu and Trisyono, 2018; Alam *et al.*, 2024). Eggs are laid in groups of 25–50, are initially white and later become black before hatching in 2–3 days. Caterpillars usually go through five instars, initially starting as pink or brown and later developing dark spots. The entire duration of the larval stage can be as short as 10–12 days. Larval survival is highest between the temperature ranging from 26 to 30°C. They begin feeding in leaf whorls, later move to tassels, ear and eventually bore into stalks after growing. They form pupae in stems, lasting 4–5 days before adult moths emerge. Adult lives up to 5–6 days, with females laying up to 1500 eggs. Females are pale yellow-brown with irregular bands across the wings, while males are darker with tapering abdomens (Nafus and Schreiner, 1991). The biology of ACB is also affected by its host plant species and varieties. In addition to their feeding behaviour, ACB larvae exhibit fascinating mobility strategies. Younger instars consume the tassel first, before moving to the ear to feed on the silk and kernels. Pupation occurs in the plant stems as the caterpillars develop by feeding on the stalks (Nafus and Schreiner, 1987). In case of limited food, larvae create silk connections (ballooning) for plant-to-plant travel or existing silk strands as trails for food and pupation (Grahame, 2022).

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Host plant range and economic impact

Among the various types of host plants, maize (*Zea mays*) is the preferred host plant of ACB (Nafus and Schreiner, 1991; Afidchao *et al.*, 2013; Shen *et al.*, 2020). Young larvae create small pinhole feeding on the leaves. Mature larvae bore into the stems, tassels and cobs. It also attacks the following plant families: Apocynaceae, Cannabaceae, Cucurbitaceae, Malvaceae, Gramineae, Solanaceae, Gingiberaceae, Polygonaceae, Phytolaccaceae, Poaceae and Zingiberaceae (Nafus and Schreiner, 1991; Ishikawa *et al.*, 1999; Grahame, 2022). Some of the alternative host plants that the ACB may attack before moving to maize crop include, *Abutilon theophrasti*, *Amaranthus* spp., *Apocynum cannabium*, *Arachis hypogaea*, *Artemisia* spp., *A. tricolor*, *Brassica oleracea*, *B. campestris*, *B. pekinensis*, *Blumea lacera*, *Capsicum annuum*, *C. frutescens*, *C. coronarium*, *Coix lacrymajobi*, *Glycine max*, *Gossypium* spp., *Helianthus annuus*, *Hibbertia scandens*, *Humulus lupulus*, *Lactuca sativa*, *Oryza sativa*, *Panicum miliaceum*, *Pennisetum glaucum*, *Pisum sativum*, *Polygonum lapathifolium*, *Proteus vulgaris*, *P. virlde*, *Ricinus communis*, *Saccharum officinarum*, *S. spontaneum*, *Setaria italica*, *Solanum melongena*, *S. nigrum*, *Sorghum bicolor*, *S. sudanense*, *S. viridis*, *Spinacia oleracea*, *Triticum aestivum*, *Urochloa mutica*, *Vigna radiata*, *V. angularis*, *Vicia faba*, *V. unguiculata*, and *Xanthium sibiricum* (Atwal, 1976; Talekar *et al.*, 1991; Tan *et al.*, 2011; Afidchao *et al.*, 2013; Chen *et al.*, 2015; Yuan *et al.*, 2015; Su *et al.*, 2016; Wei and Chen, 2020; Grahame, 2022) and grasses (barnyard grass, Johnson grass and other wild grasses).

Insect infestations severely reduce crop quantity and quality. An estimated account for 18.9 billion USD is lost annually due to invasive insect pest species, with direct losses exceeding 7.7 billion USD in China (Wan and Yang, 2016). Lepidopteran pests, particularly *O. furnacalis* with their varied lateralised behaviours (Abbas *et al.*, 2024), cause substantial economic losses in maize and sweetcorn production, with yield losses ranging from 20 to 80% (Nicolas *et al.*, 2013). Cavity counts in spikes are more reliable indicators of yield loss than larval or pupal numbers. ACB's polyphagous nature leads to extensive damage as larvae feed on various plant parts throughout corn growth stages (Sun *et al.*, 2022). The specific damage symptoms, such as stalk boring and larval frass, exacerbate fungal infections and ear contamination, significantly reducing corn quality and value (Chen *et al.*, 2013, 2015). Single larval attacks during the V10 phase can result in yield losses of 4.94%, and the number of egg masses per plant can range from 7 to 9% (Da-Lopez *et al.*, 2014; Subiadi *et al.*, 2014). According to previous studies, ACB is responsible for annual crop yield losses ranging from 6 to 9 million tons, notably causing up to 10–30% yield losses per annum in China (Wang *et al.*, 2014; Zang *et al.*, 2021) and similar damage rates likely in Myanmar (Myint *et al.*, 2023). In the Philippines, late-planted corn can suffer up to 80% ACB infestation, resulting in a 27% corn yield reduction due to 40–60% corn borer infestation (Logroño, 2006; Afidchao *et al.*, 2013).

Furthermore, ACB damage on maize ears leads to increased fumonisins levels (Li *et al.*, 2023*b*). Both ACB and ECB act as vectors for *Fusarium verticillioides* (a fungus that infects maize and known for producing fumonisins and fusarin) (Sun *et al.*, 2022; Li *et al.*, 2023*b*). In the Philippines, an economic threshold of one larva per plant was established, while field losses varied from 4.8 to 30.9% across locations (Morallo-Rejesus *et al.*, 1990). In Chinese cotton fields, larval development rates were used to forecast adult appearance, with control thresholds ranging from 1st generation, 2nd and 3rd generation with 2.8, 1.1 and 3.1 egg masses/100 plants, respectively (Liu and Yuan, 1981; Nafus and Schreiner, 1991). Larval attack patterns also depend on the sowing periods of summer maize (Wang *et al.*, 2001), highlighting the complexity of ACB management in agricultural systems.

Pest traits influence control strategies

Ostrinia spp. succeeds as a polyphagous pest due to its short generation time, high fecundity, mobility, host-switching ability and rapid development of resistance (Li *et al.*, 2023*b*). Herbivore-induced maize volatiles are crucial to the plant's ability to defend itself. The first documented elicitor, β-glucosidase, was identified in the regurgitant of the white butterfly (*Pieris brassicae*). Using β-glucosidase on leaves increased volatiles that attract parasitic wasps. Glucose oxidase (GOX) in saliva from noctuid caterpillars (*Helicoverpa zea* and *Ostrinia nubilalis*) upregulates Jasmonic acid biosynthesis pathway and late responding defence genes, such as proteinase inhibitor 2 in tomato (Tian *et al.*, 2012; Louis *et al.*, 2013). He *et al.* (2000) examined four maize volatile compounds (hyacinthin, benzaldehyde, limonene and 3-hexen-1-ol) on maize affected ACB population. Damage by ACB larvae led to significant changes in the volatile profile of maize variety 'Nongda 108' (Huang *et al.*, 2009), influencing host searching capability of conspecific gravid female adults and newborn larvae. In insect–plant interaction, host volatiles affect insects differently depending on their life stage (Holopainen, 2004). Chemical blends that resemble conspecific larvae-induced compounds may help to control ACB pests, but it is important to keep in mind that these mixtures may have distinct effects on larvae and adults (Huang *et al.*, 2009). The management of ACB is complicated by high demand of pesticide usage, resulted in the development of resistance (Fang *et al.*, 2021). Therefore, before moving further in this direction, it is important to examine the currently used approaches and their pros and cons. Additionally, novel and sustainable management strategies are needed to address the ACB economic and agricultural implications and limitations.

Management

Agroecological approaches

Agroecological approaches play a crucial role in integrated pest management (IPM) by disrupting pest life cycles and promoting natural enemy populations, making them essential for managing the ACB. Adjusting planting dates and using corn varieties with high rind penetration strength can significantly impact ACB infestations by creating unfavourable conditions for pest development (Mitchell, 1978; Guo *et al.*, 2022). Tillage practices also influence pest populations and soil health; while deep tillage harm soil quality and reduces beneficial insects, highlighting the value of zero tillage as a conservation method to maintain soil health, disrupt pest habitats and support natural enemies (Clark, 1993; Somasundaram *et al.*, 2020; Rowen et al., 2020; Jasrotia *et al.*, 2023). Balanced nutrient management is another critical factor, as excessive nitrogen use can lead to pest vulnerabilities, whereas practices such as organic manure, crop rotation and bio-inoculate-based nutrient modules improve crop productivity and stress tolerance (Altieri *et al.*, 2012; Rhioui *et al.*, 2023). In addition, ecological diversification through live mulches, intercropping and dense vegetation enhances soil quality and predator activity, reducing pest damage (Altieri *et al*., 1978; Gul *et al*., 2022; Jasrotia *et al*., 2023). Trap cropping, involving methods such as perimeter trap cropping (surrounds the cash crop) and row intercropping (with trap crops planted alternately with the main crop), attracts pests away from the main crop, reducing pesticide use and increasing yields. Techniques such as corn–soybean intercropping in specific patterns further enhance pest resistance and nutrient absorption, while 'push–pull' cropping effectively combines pest-repellent and pest-attractive plants species (Reddy, 2017; Li *et al*., 2022). Despite these, further research is needed to optimise agroecological approaches for effective ACB management.

Mating disruption

MD using sex pheromones is a promising method for managing moth pests, including the ACB, due to its species-specific and low toxicity characteristics (Lance *et al*., 2016; Harari and Sharon, 2022; Alam *et al*., 2023). Successful implementation of MD has been observed for ACB (Chen *et al*., 2013) as well as other pests such as *Conogethes punctiferalis* (Kim *et al*., 2024), *Lymantria dispar* (Lance *et al*., 2016), *Thaumatotibia leucotreta* (Steyn *et al*., 2024), *Chilo suppressalis* (Liang *et al*., 2020), *Ephestia cautella* (Walker), *E. kuehniella* and *Plodia interpunctella* (Trematerra and Colacci, 2019). Effective compounds, such as (*Z*)-12-tetradecenyl acetate (Z12-14: Ac) and (*E*)-12-tetradecenyl acetate (E12-14: Ac) have been used alone and in combination with insecticides to trap, kill and monitor ACB populations, making them a valuable component of integrated ACB management (Chen *et al*., 2016). Deng *et al*. (2023) investigated a ternary (Z12-14: Ac, E12-14: Ac and 14: Ac (*n*-tetradecyl acetate) in a ratio of 43:23:33) blend of sex pheromones which has variable roles in mediating behavioural responses to ACB, suggesting its potential integration into control strategies. Optimising pheromone trap effectiveness involves enhancing attractiveness and considering environmental factors such as temperature, crop stages and wind speed, which significantly influence moth trapping (Alam *et al*., 2023), particularly for nocturnal insects like ACB. In summary, wide-area applications of pheromone-based methods are essential for addressing ACB's high dispersal capability, maximising their effectiveness in sustainable pest control efforts.

Host plant resistance

Host plant resistance (HPR) is an effective, economical and environmental-friendly method of insect pest control. It offers several advantages, including cost-effectiveness, durability, non-pollution and adaptability to local conditions, promoting sustainable production (He *et al*., 2003). One of the most attractive aspects of HPR is its simplicity in application, requiring minimal skill, and it does not necessitate significant financial investment, which is particularly beneficial for small-scale farmers. Significant progress has been achieved in identifying and producing pest resistant varieties of crops against *O. furnacalis* (Kim *et al*., 2022). It is important to transfer resistance genes into high-yielding cultivars for diverse agro-ecosystems. In addition, varieties and hybrids released to farmers should be evaluated for pest resistance. Insect pests may be efficiently controlled by the use of genes from both wild crop relatives and novel genes including *Bacillus thuringiensis* (Bt). This method decreases chemical pesticide usage, inhibits insecticide resistance, as well as boost the beneficial organism's activity (Sharma and Ortiz, 2002). HPR is frequently integrated into broader IPM strategies for managing ACB (Kim *et al*., 2022). Hence, it is important to note that HPR should be used in conjunction with other management practices to ensure its long-term effectiveness in controlling ACB and other insect pests.

Integrated genetic approaches to pest management

Genetic technologies have transformed pest management by integrating transgenic crops and advanced biotechnological tools such as RNA interference (RNAi) and CRISPR-Cas9 (Li et al., 2021; Koo and Palli, 2024). Transgenic crops, like genetically engineered maize and cotton, produce insecticidal proteins derived from Bt, such as Cry and Vip proteins. These proteins target specific pests like ACB by binding to midgut receptors, leading to pest mortality. Since their introduction in 1996 (Li and Wu, 2022), genetically modified maize has been cultivated on 66.2 million hectares globally as of 2022 (Li *et al*., 2023*a*). Bt crops have proven effective in reducing pest populations, lowering pesticide use, minimising pollution and increasing farmer profitability (Romeis *et al*., 2019; Li *et al*., 2020). Toxins produced by Bt (Cry1Ab and Vip3Aa) maize in field studies confirm their efficacy, showing lower larval density and plant damage compared to conventional varieties (Li *et al*., 2024*b*). Additionally, Bt maize events offer season-long protection against ACB (Chang *et al*., 2013; Sun *et al*., 2021). Previous research demonstrated that the *O. furnacalis* cadherin protein (OfCad) functions as a receptor for Cry1Ac toxin, and CRISPR-Cas9-mediated knockout of the *OfCad* gene conferred moderate resistance to Cry1Ac (Jin *et al*., 2021). Furthermore, studies reveal natural variations in ACB susceptibility to active Cry1Ab Cry1F, and Cry1le (Wang *et al*., 2019, 2023), with resistance alleles present in low frequencies (Liu *et al*., 2022). Gene expression analysis has shown down-regulation of Bt resistance genes, such as aminopeptidase N1 (apn1), apn3 and abcg, in resistant strains, although no structural gene alterations were detected (Zhang *et al*., 2017). However, resistance to Bt toxins has emerged, requiring innovative approaches.

RNAi has emerged as a powerful tool for gene functional studies (Fan *et al*., 2022*a*), specifically linked to insecticide resistance (Koo and Palli, 2024; Ullah *et al*., 2023*b*) and next-generation insect pest control. Previous studies have explored the application of RNAi as a promising tool for managing the *O. furnacalis*, focusing on various aspects such as dsRNA delivery efficiency, the role of dsRNA-degrading nucleases, and the molecular mechanisms governing RNAi pathways (Zhang *et al*., 2018; Fan *et al*., 2021, 2022*a*, 2022*b*). In addition, CRISPR-Cas9, a precise gene-editing technology, further enables researchers to target pest resistance mechanisms in *O. furnacalis* (Wang *et al*., 2020; Zhang *et al*., 2023). For example, editing the ABCG4 gene in ACB has increased susceptibility to Cry1 toxins (Gao *et al*., 2022), while disrupting genes such as OfAbd-A and OfUbx has led to embryonic lethality and sterility, respectively (Bi *et al*., 2022). By combining Bt crops with RNAi and CRISPR-Cas9, researchers are developing an IPM framework to address resistance evolution and ensure sustainable pest control. This approach reduces reliance on chemical pesticides, enhances crop resilience and supports long-term agricultural sustainability.

Chemical control

ACB infestation in maize-producing areas has surged due to changing climate conditions and farming practices such as increased plantation density and altered tillage methods. Consequently,

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insecticide use to combat ACB has risen. While various insecticides have been tested against ACB on corn (Lastushkina *et al.*, 2023), their effectiveness varies. Granular insecticides applied to corn in the whorl stage can effectively manage ACB larvae (O'Sullivan and Bourke, 1975). However, research has shown that controlling ACB at this stage may not significantly reduce subsequent stalk tunnelling or yield loss (Nafus and Schreiner, 1991). In the Philippines, carbofuran application at the whorl stage without further treatment resulted in a negative net-marginal return (Felkl, 1988). Despite serious non-target effects on beneficial insects (Desneux *et al.*, 2007), chemical insecticides are widely used to control agricultural pests (Jung *et al.*, 2021), including both lethal and sublethal effects (Sun *et al.*, 2022; Ullah *et al.*, 2024*c*). Using various chemicals for pest management is a complex practice. Currently, neuro-insecticides with different target sites are regularly employed, including spinosyns, tetronic/tetramic acids, diacyl hydrazines, β-ketonitrile derivatives and diamides (Sparks *et al.*, 2019).

Population parameters have been used in many entomological studies to better demonstrate the toxic effects of pesticides, including lethal, sublethal and intergenerational impacts (Tosi *et al.*, 2022; Abbas *et al.*, 2023; Gul *et al.*, 2024; Ullah *et al.*, 2024*a*). Moreover, sublethal effects of pesticides, including malathion and deltamethrin, have been shown to influence the behaviour, communication systems and resistance mechanisms in *O. furnacalis* (Wei and Du, 2004; Zhou *et al.*, 2005; Yu *et al.*, 2018). Furthermore, these effects highlight the complexity of pesticide impact beyond direct mortality, underscoring the need for comprehensive assessments of their ecological consequences. Yang and Du (2003) also revealed sublethal effects of deltamethrin on ACB's pheromone communication system and pheromone biosynthesis activating neuropeptide-like activity. In addition, a combination of 40% chlorantraniliprole and thiamethoxam also demonstrated the best control of ACB. On the other hand, Xu *et al.* (2017) found cyantraniliprole to be the best at lethal and sublethal concentrations against ACB control. In managing *Ostrinia* sp., Huseth *et al.* (2015) explored the use of new diamide insecticides, cyantraniliprole and chlorantraniliprole, with results similar to pyrethroids when applied during pod formation. A single well-timed application of any insecticide was as effective as two applications of the same one. For IPM programmes, spinosad, *B. thuringiensis var. kurstaki* (Btk) and insect growth regulators were effective, while organophosphates and pyrethroids showed moderate to good results against ACB (Gardner *et al.*, 2011; Yang *et al.*, 2014). Imidacloprid had limited efficacy against ECB. Furthermore, an excessive and indiscriminate chemical use can lead to pest resistance, plant damage, health and environmental risks (Cutler *et al.*, 2022). To address these issues, it is crucial to establish effective and environmentally sustainable biointensive ACB management strategies in corn fields.

Biological control

An apparent alternative to the chemical management of ACB is biological control. Maize IPM relies heavily on the employment of *Trichogramma* parasitoids as ACB biocontrol agents (Zang *et al.*, 2021; Wang *et al.*, 2022). Numerous species of *Trichogramma* (Hymenoptera: Trichogrammatidae) are being utilised to manage a wide variety of moth pests with significant economic and ecological benefits. There are 12 *Trichogramma* species including *T. ostriniae*, *T. chilonis*, *T. evanescens* and *T. dendrolimi* are distributed throughout the country (China). In addition, *T. leucaniae*, *T. poliae*, *T. closterae*, *T. pintoi*, *T. ivelae*, *T. exiguum*, *T. forcipiformis* and *T. tielingensis* identified from parasitised eggs of ACB (Wang *et al.*, 2005; Zang *et al.*, 2021). Between 2005 and 2015, the use of *Trichogramma*-treated maize in Northeast China increased significantly ranging from 0.6 to 5.5 million ha (Zhang *et al.*, 2014; Huang *et al.*, 2020; Zang *et al.*, 2021). Among the diverse *Trichogramma* species, two species (*T. ostrinae* and *T. dendrolimi*) have recorded as highly promising biological control agents against ACB (Wu *et al.*, 2018; Zang *et al.*, 2021; Wang *et al.*, 2022). To produce female-biased offspring, egg parasitoids have an ability to parasitise an extensive number of eggs (Hoffmann *et al.*, 2001). Since 2012, inundative releases of *T. dendrolimi* in northeast China have reached 2.3 million hectares (ha), making it a viable biocontrol agent against ACB in China (Zang *et al.*, 2021). Several recent research (Wang *et al.*, 2005, 2014; Zang *et al.*, 2021) have highlighted the promising potential use of *T. ostriniae* (Wu *et al.*, 2018) for ACB biological control. Over 90% parasitism of ACB eggs was attained using inundative releases of *T. ostriniae* (75,000–120,000 wasps per ha), outperforming other parasitoids such as *T. dendrolimi* (Wang *et al.*, 2014; Zang *et al.*, 2021).

Expanding the horizon of potential biocontrol agents, three larval-pupal parasitoids, namely *Xanthopimpla stemmator* (Thunberg, 1824) and *Trichomma cnaphalocrosis* Uchida in family Ichneumonidae, and *Brachymeria obscurata* (Walker, 1874) in family Chalcididae has been considered to be the best against ACB (see table 1). Among these, *T. cnaphalocrosis* overwhelmingly satisfied the biological attributes of a potential biological control agent (Camarao and Morallo-Rejesus, 2003). There has been a steady increase in the distribution of *Trichogramma* parasitoids due to their long-term efficacy against ACB control. Although there has been much success with these parasitoid species, but it is still unclear which species of *Trichogramma* is most successful. Therefore, addressing these issues is imperative, especially in the realm of enhancing mass production methods for *Trichogramma* and optimising their utilisation in inundative biological control programmes.

Biopesticides

Biopesticides, comprising various Entomopathogens such as fungi, viruses, bacteria and nematodes, play a crucial role in implementing biological control strategies to combat pest-induced damage in crop plants (Marrone, 2024; Saddam *et al.*, 2024; Ullah *et al.*, 2024*a*).

Entomopathogenic fungi

Among these, entomopathogenic fungi, including *Beauveria bassiana*, *Metarhizium anisopliae*, *M. rileyi*, *Lecanicillium attenuatum*, *Trichoderma asperellum*, *Aspergillus* spp., *Fusarium* spp., *Lecanicillium lecanii*, *Nosema furnacalis*, *N. medinalis*, *N. pyrausta*, *Vairimorpha necatrix*, *Isaria fumosorosea* and *Penicillium polonicum* have demonstrated high efficacy against a wide spectrum of insect pests, such as *C. punctiferalis*, *O. furnacalis* and *O. nubilalis* (Nafus and Schreiner, 1991; Kurtti *et al.*, 1994; Zimmermann *et al.*, 2016; Majeed *et al.*, 2017; Batool *et al.*, 2020; Grahame, 2022; Wang *et al.*, 2022; Duraimurugan *et al.*, 2024; Sui *et al.*, 2024). In China, *B. bassiana*, *Aspergillus* spp., *Fusarium* spp. and *M. anisopliae* have shown promise as potential biocontrol agents for ACB (Zimmermann *et al.*, 2016; Wang *et al.*, 2022; Sui *et al.*, 2024). Notably, *B. bassiana* has been identified as a significant pathogen of *O. furnacalis* and *O. nubilalis*, with

Table 1. Asian corn borer parasitoids

		Predators\parasitoids					
S.No.	Class	Order	Family	Species	Description	Type	Source
1	Insecta	Hymenoptera	Trichogammatidae	*Trichogramma australicum* Girault (probably *T. chilotraeae* Nagaraja & Nagarkatti)	Parasitoids	Egg	Nafus and Schreiner (1991)
2				*Trichogramma chilonis* Ishii		Egg	Nafus and Schreiner (1991); Grahame (2022)
3				*Trichogramma chilotraeae* Nagaraja & Nagarkatti		Egg	Nafus and Schreiner (1991); Grahame (2022)
4				*Trichogramma closterae* Pang & Chen		Egg	Grahame (2022)
5				*Trichogramma dendrolimi* Matsumura		Egg	Grahame (2022)
6				*Trichogramma evanescens* Westwood		Egg	Nafus and Schreiner (1991); Grahame (2022)
7				*Trichogramma exiguum* Pinto & Platner		Egg	Grahame (2022)
8				*Trichogramma forcipiformis* Zhang and Wang		Egg	Nafus and Schreiner (1991); Grahame (2022)
9				*Trichogramma ivelae* Pang & Chen		Egg	Grahame (2022)
10				Trichogramma leucaniae Pang & Chen		Egg	Grahame (2022)
11				Trichogramma nubilale Ertle & Davis		Egg	Grahame (2022)
12				*Trichogramma plasseyensis* Nagaraja		Egg	Nafus and Schreiner (1991); Grahame (2022)
13				*Trichogramma pintoi* Voegele		Egg	Grahame (2022)
14				Trichogramma poliae Nagaraja		Egg	Grahame (2022)
15				*Trichogramma ostriniae* (Pang & Chen)		Egg	Nafus and Schreiner (1991); Grahame (2022)
16				*Trichogramma tielingensis* Zhang & Wang		Egg	Nafus and Schreiner (1991); Grahame (2022)
17				*Trichogramma* sp. nr. *papilionis* (Nagarkatti)		Egg	Nafus and Schreiner (1991)
18				*Trichogrammatoidea armigera* Nagaraja		Egg	Nafus and Schreiner (1991)
19			Braconidae	*Agathis agilis* Cresson		Larval	Grahame (2022)
20				*Apanteles thompsoni* Lyle		Larval	Nafus and Schreiner (1991)
21				*Aulacocentrum confusum* He & van Achterberg		Larval	Grahame (2022)
22				*Cremnops desertor* (Linnaeus)		Larval	Nafus and Schreiner (1991)
23				*Chelonus annulipes* Wesmael		Larval	Grahame (2022)
24				*Chelonus communis* Baker		Larval	Nafus and Schreiner (1991)
25				*Macrocentrus gifuensis* Ashmead		Larval	Nafus and Schreiner (1991); Grahame (2022)
26				*Macrocentrus linearis* (Nees)		Larval	Grahame (2022)
27				*Macrocentrus grandii* Goidanich		Larval	Nafus and Schreiner (1991); Grahame (2022)
28				*Microgaster tibialis* Nees		Larval	Nafus and Schreiner (1991)
29			Ichneumonidae	*Campoplex alkae* (Ellinger & Schachtleben)		Larval	Nafus and Schreiner (1991); Grahame (2022)

(*Continued*)

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Table 1. (*Continued.*)

S.No.	Class	Predators\parasitoids Order	Family	Species	Description	Type	Source
30				*Diadegma terebrans* (Gravenhorst)		Larval	Grahame (2022)
31				*Echthromorpha* sp.		Larval	Nafus and Schreiner (1991)
32				*Eriborus terebrans* (Gravenhorst)		Unknown	Grahame (2022)
33				*Eriborus sinicus* (Holmgren)		Larval	Nafus and Schreiner (1991); Grahame (2022)
34				*Eriborus terebrans* (Gravenhorst)		Larval	Nafus and Schreiner (1991)
35				*Temelucha philippinensis* Ashmead		Unknown	Grahame (2022)
36				*Trichomma cnaphalocrocis* Uchida		Larval-Pupal	Grahame (2022)
37				*Trathala flavoorbitalis* (Cameron)		Larval	Nafus and Schreiner (1991); Grahame (2022)
38				*Exeristes roborator* (Fabricius)		Pupal	Nafus and Schreiner (1991); Grahame (2022)
39				*Itamoplex* sp.		Pupal	Nafus and Schreiner (1991)
40				*Phaeogenes nigridens* Wesmael		Pupal	Nafus and Schreiner (1991)
41				*Trichomma cnaphalocrocis* Uchida		Larval-Pupal	Nafus and Schreiner (1991)
42				*Xanthopimpla punctata* (Fabricius)		Larval-Pupal	Nafus and Schreiner (1991); Grahame (2022)
43				*Xanthopimpla modesta* (Smith)		Unknown	Grahame (2022)
44				*Xanthopimpla stemmator* (Thunberg)		Larval-Pupal	Nafus and Schreiner (1991); Grahame (2022)
45			Chalcididae	*Brachymeria albotibialis* (Ashmead)		Pupal	Nafus and Schreiner (1991); Grahame (2022)
46				*Brachymeria euploeae* (Westwood)		Pupal	Nafus and Schreiner (1991)
47				*Brachymeria lasus* (Walker)		Pupal	Nafus and Schreiner (1991); Grahame (2022)
48				*Brachymeria obscurata* (Walker)		Pupal	Nafus and Schreiner (1991); Grahame (2022)
49				*Chalcis euploeae* Westwood		Pupal	Nafus and Schreiner (1991)
50			Eulophidae	*Tetrastichus inferens* Yoshimoto		Pupal	Nafus and Schreiner (1991); Grahame (2022)
51		Diptera	Tachinidae	*Exorista tritaeniata* Rondani		Larval	Nafus and Schreiner (1991)
52				*Lydella thompsoni* Herting		Larval	Nafus and Schreiner (1991); Grahame (2022)
53				*Nemorilla floralis* (Fallén)		Larval	Nafus and Schreiner (1991)
54				*Paradrino laevicula* (Mesnil)		Larval	Nafus and Schreiner (1991)
55				*Pseudoperichaeta erecta* (Coquillett)		Larval	Nafus and Schreiner (1991)
56				*Tachinid* sp.		Larval	Nafus and Schreiner (1991)
57				*Tachinid* sp.		Pupal	Nafus and Schreiner (1991)
58		Hemiptera	Harpactoridae	*Phemius tibialis* (Westwood)	Predators	Larval	Nafus and Schreiner (1991)
59				*Sphodronyttus erythropterus* (Burmeister)		Larval-Pupal	Nafus and Schreiner (1991)
60			Anthocoridae	*Orius* sp.		Egg	Nafus and Schreiner (1991)
61				*Onus niobe* Herring		Egg	Nafus and Schreiner (1991)

(*Continued*)

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Table 1. (*Continued.*)

S.No.	Class	Predators\parasitoids Order	Family	Species	Description	Type	Source
62			Pentatomidae	*Menida formosa* (Westwood)		Egg	Nafus and Schreiner (1991)
63				*Eocanthecona furcellata* (Wolff)		Larval	Nafus and Schreiner (1991); Grahame (2022)
64		Dermaptera	Chelisochidae	Chelisoches morio (Fabricius)		All stages	Nafus and Schreiner (1991)
65				*Proreus simulans* (Stål)		All stages	Nafus and Schreiner (1991)
66			Carcinophoridae	*Euborellia annulipes* (Lucas)		Larval-Pupal	Grahame (2022)
67				*Euborellia stali* (Dohrn)		Larval-Pupal	Nafus and Schreiner (1991)
68			Labiduridae	*Nala lividipes (Dufour)*		Larval	Grahame (2022)
69				*Labidura riparia* (Pallas)		All stages	Nafus and Schreiner (1991); Grahame (2022)
70		Coleoptera	Histeridae	*Carphophyllus foveicollis* Murr.		Larval-Pupal	Nafus and Schreiner (1991)
71			Coccinellidae	*Anisosticta kobensis* Lewis		Unknown	Grahame (2022)
72				*Harmonia octomaculata* (Fabricius)		Larval	Grahame (2022)
73				*Menochilus sexmaculatus* (Fabricius)		Egg	Nafus and Schreiner (1991)
74				*Micraspis crocea* (Mulsant)		Egg	Nafus and Schreiner (1991)
75			Carabidae	*Plochnius* sp.		Larval	Nafus and Schreiner (1991)
76				*Chaenius* sp.		Larval	Nafus and Schreiner (1991)
77		Hymenoptera	Formicidae	*Solenopsis geminata* (Fabricius)		All stages	Nafus and Schreiner (1991)
78				*Monomorium minutum* Mayr		Egg	Nafus and Schreiner (1991)
79			Sphecidae	*Sceliphron madraspanatum cospicillatum*			Nafus and Schreiner (1991)
80	Arachnida	Araeneida	Argiopidae	*Araneus inustus* (L. Koch)		Larval	Nafus and Schreiner (1991)
81			Oxyopidae	*Oxyopes javanus* Thorell		Larval	Nafus and Schreiner (1991)
82			Theridiidae	*Theriid* sp.		Larval	Nafus and Schreiner (1991)
83			Anystidae	*Anystis* sp.		Egg	Nafus and Schreiner (1991)

occurrences documented mainly in the USA (Steinhaus, 1951, 1952; Steinhaus and Marsh, 1962; Bing and Lewis, 1993; Cherry *et al*., 1999; Inglis *et al*., 2000; Phoofolo *et al*., 2001). Its presence in corn ecosystems, including crop residue, contributes to natural pest control, with potential for integration into environmentally sustainable corn cropping systems (Wang *et al*., 2022). In another study, Sui *et al*. (2024) also emphasised the promising potential of using entomopathogenic fungi as endophytes in ACB management strategies under elevated CO_2 conditions.

Entomopathogenic virus

Entomopathogenic viruses, also known as insect-killing viruses, are a recent development in pest control, with various types engineered specifically to target agricultural pests globally (López-Ferber, 2020; Singh *et al*., 2024). Although natural ACB populations have not been found to harbour viruses, the laboratory and field studies have confirmed the pathogenicity of two nucleopolyhedroviruses (NPVs), *Autographa californica* multicapsid nucleopolyhedrovirus (AcMNPV) and *Rachiplusia ou* multicapsid nucleopolyhedrovirus, against *O. nubilalis* (Lewis and Johnson, 1982). Baculoviruses within the microbial control agents have garnered attention for their potential as bioinsecticides due to their specific virulence against hosts and enhanced safety for vertebrates (Ferrelli and Salvador, 2023). Baculoviruses employ various strategies to suppress host defence mechanisms, including apoptosis, melanisation and RNAi (Ji *et al*., 2022). AcMNPV stands as a potential biocontrol agent against ACB, inhibiting Phenoloxidase activity, amidase activity and inducing the expression of ACB serpin-4 protein (Ji *et al*., 2022). In other members of the Crambidae family, such as the sugarcane borer, *Diatraea saccharalis*, two viruses, densovirus and granulovirus (GV), have been detected (Meynadier *et al*., 1977; Pavan *et al*., 1983). Additionally, various NPVs and GVs have been recorded in cereal stem borers from Africa and Asia (Cherry *et al*., 1999; Hernández-Velázquez *et al*., 2012).

Entomopathogenic bacteria

Entomopathogenic bacteria are extensively employed biopesticides for insect control (Duraimurugan *et al*., 2024). In initial studies, Paillot (1928) isolated the bacteria labelled as 'Coccobacillae' and

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'Micrococcus', but these were found to be non-infectious to certain *Ostrinia* species larvae. Furthermore, entomopathogenic bacteria, including Alcaligenes, probably *Achromobacter*, *Bacillus* and *Pseudomonas* (*P. aeruginosa*), were recorded from diseased specimens (Steinhaus, 1951, 1952; Steinhaus and Marsh, 1962). These findings align with the presence of bacteria (*Alcaligenes* sp., *Achromobacter* sp., *B. thuringiensis*, *Enterobacter* sp., *Hafnia* sp., *Serratia* sp. and *Staphylococcus aureus*) in natural *Ostrinia* populations (Zimmermann *et al.*, 2016). Mixed infections with *Fusarium* spp., *N. pyrausta* and nematodes have also been observed. *Bacillus thuringiensis* has emerged as a potent biological control agent against *C. punctiferalis* and ACB (Ma *et al.*, 2008; Duraimurugan *et al.*, 2024) and has been detected in field populations, particularly in summer maize areas (He *et al.*, 2002). Previous studies have revealed the presence of bacterial endosymbionts, *Spiroplasma* and *Wolbachia*, in *Ostrinia* species, influencing sex determination mechanisms (Tabata *et al.*, 2011; Hornett *et al.*, 2022). Various bacteria were also identified in *Ostrinia* sp. larvae from different maize fields, including *Pseudomonas aeruginosa*, *Brevundimonas aurantiaca*, *Chryseobacterium formosense*, *Acinetobacter* sp., *Microbacterium thalassium*, *Bacillus megaterium*, *Serratia* sp., *Ochrobactrum* sp., *Variovorax paradoxus*, *Corynebacterium glutamicum*, *Paenibacillus* sp., *Alcaligenes faecalis*, *Microbacterium testaceum*, *Leucobacter* sp. and *Serratia marcescens*. Among these, *P. aeruginosa*, *Serratia* sp., *V. paradoxus* and *S. marcescens* exhibited the highest mortality rates against larvae (Secil *et al.*, 2012). These bacteria have also been isolated from other corn borer species, such as *Diatraea grandiosella* and *D. crambidoides* (Inglis *et al.*, 2000).

Entomopathogenic nematode

Entomopathogenic nematodes (EPNs) hold considerable promise for their role in the biological control (Toepfer *et al.*, 2024). In an earlier compilation, various nematodes known to target ECB and ACB (He *et al.*, 1991; Chau *et al.*, 2022). These nematodes include *Diplogaster brevicauda*, *Hexamermis meridionalis*, *Heterorhabditis indica* and *Steinernema Neoaplectana* glaseri (in laboratory settings). Additionally, *Steinernema feltiae* stands out as an excellent candidate for developing conservation-based biological control strategies against ACB, as suggested by He *et al.* (1991). Chau *et al.* (2022) further reported that four indigenous EPN strains – namely, S-PQ16 (*Steinernema* sp. PQ16), S-TX1 (*S. sangi* TX1), S-DL13 (*S. siamkayai* DL13) and H-NT3 (*H. indica* NT3) – demonstrate substantial potential in reducing ACB's virulence and reproductive capabilities.

Insectivorous birds

Insectivorous birds are effective natural predators of crop-damaging pests, significantly contributing to pest management in agriculture (Morse, 1971; Nyffeler *et al.*, 2018; Díaz-Siefer *et al.*, 2022; Jerilyn *et al.*, 2024). These birds have been observed reducing larval populations by up to 84% (Jones *et al.*, 2005), with species like the black drongo, house sparrow, blue jays, cattle egret, rosy pastor and mynah commonly targeting large larvae in crops. Borderline trees, offering perches and shelter, enhance farm biodiversity and support bird populations (Altieri *et al.*, 2012). These bird species are adept at extracting ACB larvae from maize plant whorls and husks.

Birds such as red-winged blackbirds are known to prey on both parasitised and non-parasitised larvae (Jones *et al.*, 2005), with perching opportunities vital for maximising their pest control impact. To support this, fast-growing plants should be cultivated within maize fields, providing strong perches for birds from the vegetative stage through crop maturity. In addition, recent studies have reinforced the role of birds in pest control, suggesting that maintaining bird-friendly habitats can reduce the reliance on chemical pesticides while boosting crop yields (Karina *et al.*, 2020; Díaz-Siefer *et al.*, 2022; Jerilyn *et al.*, 2024). In summary, integrating bird perches in agricultural ecosystems offers a promising, eco-friendly method for managing pests like ACB, contributing to sustainable farming practices.

Botanical-based insecticides

Many plants possess insecticidal properties, leading to the development of botanical insecticides, which can be extracted or synthesised from plants and minerals (Isman, 2006). As demand for environmentally friendly pest management in edible crop production rises, botanical solutions are increasingly being explored. Botanical insecticides are considered effective alternatives to synthetic chemical pesticides, as they have minimal environmental and human health impacts (Isman, 2006). This has led to growing interest in botanical pest management strategies (Isman, 2020; Abbas *et al.*, 2022; Dar *et al.*, 2022; Surajit *et al.*, 2023). Ginseng, a traditional Chinese medicine, is one example of a widely used botanical remedy in Asia (Liu *et al.*, 2020).

In many developing countries, farmers opt for eco-friendly, cost-effective botanical methods to manage pests in field crops and stored goods. Botanical extracts such as *Milletia ferruginea*, *Azadirachta indica*, *Croton macrostachyus*, *Jatropha curcas*, *Phytolacea docendra*, *Chrysanthemum cinerariifollium* and *Nicotiana tabacum* have shown success in pest control (Schmutterer, 1985; Isman, 2006; Isman, 2020; Dar *et al.*, 2022). Azadirachtin, derived from neem, is particularly promising for managing ACB, with research showing its effects on ACB larvae's physiology and histopathology after exposure to azadirachtin-treated diets (Shinfoon *et al.*, 1985). Additionally, Liu *et al.* (2020) reported that panaxadiol saponins treatment has also been shown to cause subtle variations in the global transcriptional state of *O. furnacalis*. Therefore, botanical insecticides are likely to play a crucial role in addressing the rapidly growing demand for sustainable control options against *O. furnacalis*.

Conclusion and recommendations

In conclusion, the ACB, *O. furnacalis*, remains a devastating pest affecting maize production across the globe, particularly in Asian countries. Despite extensive research efforts, several key aspects of ACB's ecology and management still require further exploration to mitigate its impact in invaded regions. Current management approaches rely heavily on agroecological methods, biotechnology and broad-spectrum chemical insecticides, which are often unsustainable and undesirable in many affected countries.

To advance sustainable ACB management, we propose several key recommendations for future research:

1. *Tailored pheromones:* Develop region-specific pheromones to enhance ACB monitoring, particularly in non-invaded and temperate areas.
2. *Seasonal spread modeling:* Create models for seasonal ACB spread and its impact in temperate and tropical Asian regions.

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3. *Yield loss relationships:* Investigate the intricate links between ACB infestation, leaf and ear damage, yield loss and variations based on crop stage and agroecological conditions.
4. *Biological control:* Explore biological control methods, including the introduction of natural enemies, even in native regions.
5. *Sustainability focus:* Prioritise research on sustainable use of Bt maize, minimise the impact of chemical insecticides on the environment, assess social implications and emphasise cultural relevance in IPM recommendations.
6. *AI and machine learning in sustainable pest management:* The advent of digitalisation such as power of artificial intelligence (Kariyanna and Sowjanya, 2024; Venkatasaichandrakanth and Iyapparaja, 2024), machine learning (Mittal *et al*., 2024; Qin *et al*., 2024) and deep learning (Chithambarathanu and Jeyakumar, 2023; Dong *et al*., 2024), smart agriculture can revolutionise pest control practices, making them more targeted, efficient and environmentally friendly, while ensuring optimal crop health and productivity (Guo *et al*., 2024).

These targeted efforts will guide the development of effective and sustainable ACB management strategies, safeguarding maize crops and food security.

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