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REVIEW ARTICLE

CLIMATE CHANGE AND INSECT PEST DYNAMICS IN MAJOR CEREAL CROPS: MECHANISMS, SHIFTING PATTERNS, AND ADAPTIVE MANAGEMENT IMPERATIVES FOR SUSTAINING GLOBAL FOOD SECURITY

Anika Yesmin Sorna[a], Md. Tanvir Rahman[b], Arina Akter Nupur[a], Farhana Yeasmin[c], Md. Mamunur Rahman[a]*

[a] *Department of Entomology, Gazipur Agricultural University, Bangladesh*
[b] *Department of Genetics and Plant Breeding, Gazipur Agricultural University, Bangladesh*
[c] *Department of Agricultural Extension and Rural Development, Gazipur Agricultural University, Bangladesh*
***Corresponding author email: mamun@gau.edu.bd**

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ABSTRACT

Climate change is profoundly reshaping the ecological dynamics of insect pests, posing significant threats to global crop production and food security. This review synthesizes current knowledge on how rising temperatures, altered precipitation patterns, and elevated atmospheric CO_2 levels influence pest biology, population dynamics, geographic distribution, and interactions with host plants and natural enemies. Evidence indicates that many insect pests are experiencing increased voltinism, range expansions, and prolonged activity periods, while pest-crop interactions are becoming more unpredictable across agroecological zones. Invasive species are emerging as dominant threats in newly suitable habitats, often outpacing the adaptive capacity of indigenous biocontrol agents. Moreover, climate variability disrupts pest phenology, weakens the efficacy of conventional management strategies, and complicates forecasting models. Crop-specific case studies highlight how key staples such as rice, wheat, maize, and barley are increasingly vulnerable to pest outbreaks under shifting climatic regimes. We emphasize the urgency of integrating climate-adaptive frameworks into pest management, including the deployment of predictive modelling tools, host plant resistance breeding, and ecologically-based strategies that enhance agroecosystem resilience. This review underscores the necessity for a paradigm shift in pest management—from reactive control to proactive, climate-informed interventions—to safeguard crop productivity in a warming world.

KEYWORDS

insect pests, agroecological, Crop-specific, agroecosystem resilience

1. INTRODUCTION

1.1 Overview of climate change and its effects on ecosystem

One of the major concerning conditions around the world is climate change which indicates long-term shifts in global and regional climate pattern mainly caused by human activities. Since the era of the Industrial Revolution, change is occurring in temperature as well as precipitation pattern, the world is facing more weather extremes. It has been found that the global temperature has been increased by over 1.1°C since pre-industrial times (Johnsen et al., 2020). Terrestrial biomes like tropical forests experience increased drought stress which reduce their capacity to sequester carbon (Nath et al., 2024). Extreme weather events like high temperatures and intense storms further disturbs habitats and reduces genetic diversity (Lucas et al., 2024). All these effects in combination compromise ecosystem services like water purification, soil fertility, and natural pest control as well as threaten the stability of crop-insect interactions essential for food production.

Climate change directly and indirectly influences cereal crops and their associated insect communities in the agricultural systems. Elevated temperatures accelerate insect metabolic rates and reproductive cycles. Heat stress can disrupt critical crop growth stages in different cereal crops. For example, pollen viability in wheat and grain filling in maize is negatively affected in moderate to excessive heat which can reduce yields by up to 10–15% (Qian et al., 2025). Nitrogen content in plants can be reduced due to increase in CO_2 level in the atmosphere and production of defensive compounds against the herbivore in plant is declined which can increase susceptibility to pest attack (Johnson et al., 2020).

1.2 Importance of cereal crops in global food security

Cereal crops are a group of grass species cultivated primarily for their edible grains and these crops serve as staple foods for a large proportion of the global population. These include rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor*), and others are minor cereals. The four key dimensions of food security are availability, accessibility, utilization, and stability. In most countries of the world, including developing nations, cereal crops are the foundation of dietary intake ensuring food availability and access (Pingali, 2012).

1.3 Role of insect pests and beneficial insects in cereal crop production

Insect pests are a major biotic constraint in cereal crop production. They cause significant yield and quality losses as they may directly damage the plant tissues (e.g., leaves, stems, grains). In some cases, they act as vectors

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for plant pathogens and spread disease from affected plants to healthy plants resulting serious crop damage (Seni and Halder, 2022). In regions of the world where resources are limited, minor pest infestations can even cause a serious threat to food security and farmer livelihoods.

Different cereals crops are affected by various insect pests, but there are some insect species which acts as generalist. Globally wheat (*Triticum aestivum*) is the most widely cultivated as well as most consumed cereal crop (Gooding, 2023). The Hessian fly (*Mayetiola destructor*) severely damages wheat seedlings as they feed on stem tissues which eventually results stunting growth and increasing susceptibility to abiotic stresses (Tadesse et al., 2022). Various aphid sucks sap from wheat plant and in the same time injects toxins which leads to leaf curling and reduced photosynthesis (Shahzad et al., 2019). Rice (*Oryza sativa*) is another major staple food crop which faces threats from the rice stem borer (*Chilo suppressalis*) as this pest attacks rice tillers (Horgan et al., 2021). Maize (*Zea mays*) faces devastating attack from the fall armyworm (*Spodoptera frugiperda*) which devours leaves and ears while the maize weevil (*Sitophilus zeamais*) infests stored grain and causes post-harvest losses (Rosentrater, 2022). Barley (*Hordeum vulgare*) and minor cereals like sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) are similarly vulnerable to pests such as barley aphids (Rhopalosiphum *padi*) and sorghum shoot fly (*Atherigona soccata*) (Todkar et al., 2023).

While insect pests pose significant threats to cereal crops there are also some beneficial insects which are often termed natural enemies. Some predators are generalist for example- lady beetles (Coccinellidae), lacewings (Chrysopidae), and hoverflies (Syrphidae). They prey on aphids, lepidopteran larvae, and other pests in wheat, maize, and rice fields thus play a crucial role in cereal crop production. In rice field, the mirid bug *Cyrtorhinus lividipennis* preys on brown planthopper (*Nilaparvata lugens*) eggs, and spiders (e.g., *Lycosidae*) act as key predators of leafhoppers and stem borers (Zhong et al., 2023). In maize, the egg parasitoid *Trichogramma pretiosum* reduce larval damage as it targets fall armyworm (*Spodoptera frugiperda*) eggs (Jin et al., 2021). The efficacy of these beneficial insects depends on habitat diversity and sustainable farming practices.

2. CLIMATE CHANGE AND AGRICULTURAL ECOSYSTEM

Climate change is a complex, multifaceted phenomenon and both anthropogenic and natural factors bring changes in the climatic condition. There are certain components which affects more than others and these are temperature variations, rising atmospheric CO_2 levels, and changes in precipitation patterns. These elements shift the weather pattern as they interact dynamically which affects ecosystem functions and eventually disrupts overall environmental stability (Calvin et al., 2023). One of the most evident indicators of climate change is the rise in global temperatures resulting intense heatwaves, altered seasonal cycles, and disruptions in natural ecosystems. Temperature extremes affect biodiversity as it increases desertification also accelerates ice sheet melting which leads to rising sea levels (Hansen et al., 2023).

The concentration of atmospheric CO_2 has exceeded 420 ppm, critical in plant growth and oceanic carbon sequestration and its excessive accumulation contributes to ocean acidification, increased global temperatures, and disruptions in weather patterns (Doney et al., 2020). The hydrological cycle is becoming more erratic with extreme weather events such as hurricanes, cyclones and flash floods increasing in frequency. These shifts disrupt freshwater availability, affect groundwater recharge rates, and alter the distribution of vegetation and wildlife across different ecosystems (Padarian et al., 2022). Prolonged dry spells also contribute to desertification, land degradation, and an increased risk of wildfires, particularly in Mediterranean, Australian, and Californian ecosystems (Abatzoglou et al., 2019).

2.1 Impact of climate variability on cereal crop physiology and yield

The growth and development of cereal crops are highly sensitive to climate variability, especially during critical stages such as grain filling hampering two main carbon sources: current carbohydrate production via photosynthesis and the redistribution of assimilates from vegetative tissue reserves. These processes are directly affected by environmental stressors like drought, heat, and soil salinity all of which hinder carbon metabolism and reduce crop productivity.

Heat stress (HS) and drought are among the most damaging climate variables. High temperatures induce the production of reactive oxygen species (ROS) in various cell organelles such as chloroplasts and mitochondria leads to membrane damage, protein degradation, and enzyme inactivation all of which impair plant function and reduce overall plant viability (Shelake et al., 2024). Low light stress which occurs in cloudy or rainy conditions reduces photosynthetic efficiency further inhibiting carbon fixation and delaying crop growth (Wang, 2024). Stomatal regulation is another major physiological response to heat stress- limits the intake of carbon dioxide which slow down photosynthesis (Marchin et al., 2022). The cumulative effect of physiological disruptions during critical growth stages is a reduction in both the quantity and quality of cereal crop yields.

In the case of rice high temperatures during critical growth stages such as flowering and grain filling can lead to disruptions in photosynthesis, nutrient uptake, and water balance (Yu et al., 2024). Maize and wheat are also sensitive to heat stress during their reproductive stages. In maize heat stress at the flowering stage can damage reproductive tissues and lead to reduced seed set which results in lower yield (Li et al., 2022).

The overall effect of climate variability on crop yield can be devastating as it is estimated that a 1°C increase in global temperature could reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4% (Djalovic et al., 2024b). Heatwaves, droughts, and unpredictable weather patterns are expected to become more frequent which creates substantial challenges for cereal crop production worldwide.

2.2 Shifts in agricultural zones due to climate change

Climate change is altering temperature and precipitation patterns globally which results geographic shifts in agricultural suitability. Rising global mean surface temperatures (GMST) and intensified aridity are redefining traditional growing regions. As a result, the areas which are considered historically fertile face declination in productivity. In the same time the areas which seemed to be less fertile are providing more crop yield than before. For example, temperate regions with non-dry summers are transitioning to drier climates that compromises irrigated systems which are critical for staple crops like rice and wheat (Straffelini and Tarolli, 2023). Warmer temperatures are pushing agricultural zones poleward and to higher elevations. Equatorial regions are experiencing reduced crop suitability due to heat stress and erratic rainfall which threats food security in vulnerable countries(Sarma et al., 2024). Globally 20–30% of current cropland may become unsuitable by 2100 under high-emission scenarios while new arable zones emerge in colder regions (e.g., Canada, Siberia) with limited infrastructure and soil fertility (European Environment Agency., 2019). This transition risks local economies which displaces farming communities and exacerbates geopolitical tensions over resources.

3. CLIMATE CHANGE AND INSECT DYNAMICS

3.1 Effects of Rising Temperatures on Insect Physiology and Life Cycles

Rising global temperatures are two important factors which affects insect physiology and life cycles. A 10°C increase in temperature can double metabolic rates. This increased metabolic rate accelerates their feeding, development, and mobility (Sunil et al., 2023). Multivoltine pests like aphids (*Myzus persicae*) complete up to five additional generations annually under a 2°C warming scenario that is driven by shortened developmental times (Subedi et al., 2023). The large cabbage white butterfly (*Pieris brassicae*) shows faster larval development as well as increased fecundity in warmer conditions. These increased metabolic activities leads to rapid population surges that outpace natural predator responses (Nitta et al., 2024).

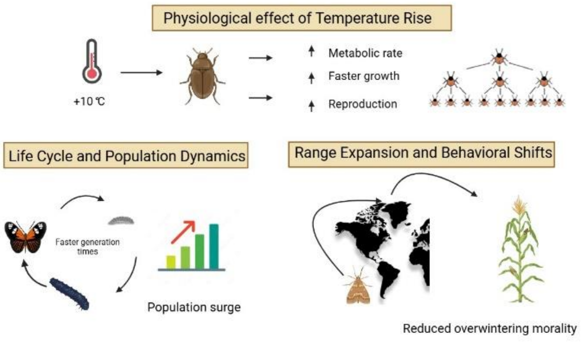

Figure 1: A conceptual illustration demonstrating impacts of climate change in the physiology and life cycle of insects. Rising temperatures accelerate insect metabolism and reproduction which leads to increased generations per season. Insects are becoming able to complete life cycle faster which results population surges. Overwinter survival is enhancing due to warmer winter and insects are expanding their ranges towards temperate regions.

3.2 Changes in Insect Population Density and Distribution

Insects are critical to ecosystem services that's why are experiencing significant shifts in population density and geographic distribution due to climate change. The life cycle of insects and their survival rates are altered due to global temperature rise as well as various climate extremes. These phenomenon also bring negative effects on their abundance and spatial ranges (Harvey et al., 2020).

Voltinism is a phenomenon where elevated temperatures accelerate developmental rates and extend growing seasons which enables many species to produce additional generations in annual. It has been found that even modest temperature increases of 1 to 2°C can elevate seasonal voltinism by 10 to 25% which results high increase of agricultural pests such as *Drosophila suzukii* (Harvey et al., 2023). Tropical insects often occupy narrow thermal niches and face heightened mortality risks under prolonged heatwaves which leads to population declines in pollinators. This phenomenon has been found in stingless bees (*Meliponini*) (Szyniszewska et al., 2024a).

Climate change also bring changes in the geographic distributions across the globe. Oriental fruit fly (*Bactrocera dorsalis*) is an insect pest which is currently bound in subtropical zones due to cold stress. It is predicted that its range is about to extend into southern Mediterranean Europe and the southeastern United States if the warming of the world continues to grow in the current state. This expansion correlates with higher pest densities in newly colonized areas which highly threats agricultural systems (Nitta et al., 2024). All these projections are not completely certain because bioclimatic models often overlook biotic interactions for example predator-prey dynamics which may buffer against thermal extremes (Szyniszewska et al., 2024b).

3.3 Alterations in Pest Behavior, Migration, and Overwintering

Heat stress impacts negative effects on insect survival and reproductive behavior. It has been found that brief exposure (<1 hour at 36°C) can induce sterility in multiple insect orders which includes Diptera, Hymenoptera, and Coleopter and this susceptibility may vary in different stages of life of insects (Harvey et al., 2023). It has been found that heat waves can reduce sperm viability in male thus negatively affect insect fertility (Campion et al., 2023). Their offspring also show reduced reproductive fitness as well as reduced lifespan which can be termed as transgenerational impact. Female insects are less affected due to heat stress but they cannot shield stored sperm from thermal damage (Walsh et al., 2022).

Biodiversity hotspots (e.g., islands, mountains) face heightened vulnerability due to limited corridors for species tracking shifting climates, exacerbating ecosystem imbalances (Leclerc et al., 2020). Warmer winters disrupt diapause, a critical survival strategy. Many insects require chilling periods to terminate diapause, but rising temperatures delay or prevent this process. Extended growing seasons in southern regions allow timely maturation to adulthood (Subedi et al., 2023). Developmental traps also emerge: unseasonably warm autumns may trigger additional pest generations incapable of surviving winter, as seen in Lepidoptera (Harvey et al., 2023). Premature diapause entry depletes energy reserves, reducing spring fecundity and destabilizing agroecosystems.

4. INSECT-PLANT INTERACTION UNDER CLIMATE CHANGE

4.1 Modification of host plant phenology and nutritional profiles

Plant phenology is one of the most accurate indicators of climate change because it is heavily influenced by climate (Potter & Olaoye, 2024). Climate change has become a critical factor influencing plant phenology, the study of the timing of seasonal biological events. These phenological shifts have cascading effects on ecological interactions, including pollinator activity and plant-pollinator synchronization.

In forests, species are altering their phenology to track warming temperatures. It is found that a mean advance of flowering onset of 7.1 d per 1°C warming, where Warm-adapted species exhibited greater advances (Lorer et al., 2024). Climate warming has shifted plant phenology of rice-length of growing period (GP) increased by 3.24 ± 0.15 days/decade for single rice, 1.90 ± 0.22 days/decade for early rice and 0.47 ± 0.14 days/decade for late rice (Zhang et al., 2022).

4.2 Influence on insect feeding behavior and reproductive success

Climate change has crucial impacts on agriculture as well as agricultural insect pests. Increased CO2 levels affect plant physiology as it increases photosynthetic activity. Plants grown under elevated CO2 cause a change in the chemical composition of leaves, which brings change in the nutritional quantity of foliage. As C:N ration is altered, some pest must consume more plant tissue to obtain an equivalent level of food. These results increased levels of plant damage by foliage feeders like caterpillars, miners and chewers. In elevated CO2 concentrations aphids are getting benefitted from the condition (Tora et al., 2023). For annual plants, higher temperatures, CO2 and drought stress increase foliar herbivory (Anderson et al., 2021).

4.3 Indirect effects on pollination and natural enemies

Bee is one of the most important pollinator, bee-pollinated crops contribute to one-third of the total human dietary supply (Khalifa et al., 2021). Climate change affects negatively bees by impacting their food resources. Pollinators' geographical distribution and abundance are being redefined by changing climatic conditions (Kumar et al., 2024). Due to global warming, increased global temperatures and the intensity and frequency of precipitation and wildfires were negatively correlated with pollen diversity (Balmaki et al., 2024).

Climate change may affect negatively on biological control agents or natural enemies. Due to climate change, temperature change occurs which brings temporal desynchronization (Huang et al., 2023). Insect phenology is affected by climate change, resulting asynchronies as species from different trophic levels have different responses rates to climate change. Due to climate change, crop distribution ranges are predicted to shift, herbivores may track changes and migrate to new areas (Xu et al.,2024).

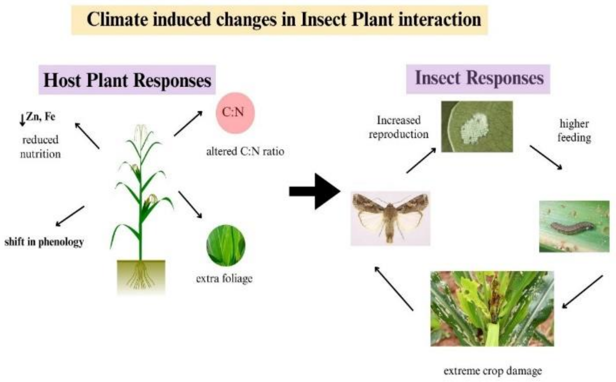

Figure 2: Climate induced changes in the interaction of plants and insects. Elevated CO2 and other climate related factors change the C:N ratio in plant, reduce essential nutritional compound and increase foliage altering insects' feeding habit, along with increasing generation leading to extreme crop damage.

5. CASE STUDIES : MAJOR CEREAL CROPS

5.1 Wheat

Wheat (*Triticum aestivum*) is one of the most widely cultivated as well as consumed cereal crops around the world and it contributes more than 20% of the daily dietary protein and caloric intake for humans (Mao et al., 2023). Originating from the Fertile Crescent, Wheat is a crop which has adapted to vast agro-ecological zones and as it is among the few crops that can be found arid and semi-arid regions. The global population is projected to reach 9.7 billion by 2050. In the meantime, wheat demand is expected to increase by nearly 60%. Due to various stresses related to climate, wheat production could reduce by up to 29% (Lankford et al., 2023). There are various climate related stresses which has threaten production of wheat. Among them rising temperatures, alteration in the precipitation patterns, elevated levels of atmospheric CO_2 are the most prominent (Bhanbhro et al., 2024).

5.1.1 Response of wheat pests to climate change

There are various biotic stresses and the insect pests are major threats among them. Aphids are one of the most destructive pests of wheat. It has been found that in the spring and summer months the fecundity of aphids has increased due to warmer climate. In the meantime, the winter months are becoming less cold which results high number of population of aphids which brings more viral diseases (Szyniszewska et al., 2024b). This condition becomes more complicated due to elevated CO_2 as insects feed more in this condition. The overall situation leads to increased herbivory because elevated CO_2 reduce plant nutrition (Sunil et al., 2023).

Climate change also affects insect phenology- Aphids show earlier spring emergence and delayed onset of winter diapause which increases the number of generations (voltinism) within a growing season (Ma et al., 2024). Change in the intensity and frequency of rainfall also can influence the rate of the survival of insects. Extreme rainfall can wash away pests which have small bodies such as aphids and whiteflies. If soil remains saturated for long time it negatively impacts the stages of pests which needs to be done in the soil for example, larvae diapause (Skendžić et al., 2021). The Hessian fly is another devastating pest of wheat in the world now. The lifecycle as well as stages of the developments are mainly controlled by temperature and humidity (Maldani et al., 2024).

5.2 Rice

Rice is one of the major staple food crops around the world. For a long period of time research is ongoing to increase the yield of the rice crop so that it can fulfill the demand of global population. But it has been found that adverse climatic factors especially heat stress and drought are posing significant threat in rice production. Grain yield decreases by about 7% for 1 °C increase in night time temperature if 22 °C is considered as optimum temperature. In the same time 1 °C increase in day time temperature leads to decrease in grain yield by about 6% when temperature exceeds 28 °C (Su et al., 2023).

The increasing unpredictability of weather patterns and misuse of insecticides has increased the resurgence of rice planthopper outbreaks for example *Nilaparvata lugens* and *Sogatella furcifera*. These devastating attacks have resulted in crop failures affecting more than 33,000 hectares in recent years (Sunil et al., 2023).

5.2.1 Changes in brown plant hopper dynamics and associated viruses

Since the green revolution the brown planthopper (*Nilaparvata lugens*) has been arrived as a major pest of rice plant. It's feeding habit cause hopperburn, acts as a vector for plant pathogenic viruses which includes the Rice Grassy Stunt Virus (RGSV) and Rice Ragged Stunt Virus (RRSV) (OISHI et al., 2024). Elevated CO_2 levels have been shown to enhance BPH proliferation dramatically, with populations increasing from 121 hoppers/hill under ambient conditions to 435 hoppers/hill under enriched CO_2 levels (Sunil et al., 2023). BPH infestations are closely linked to climate variability, threatening virtually all rice varieties.

Peak BPH infestations during the generative phase of rice result in marked reductions in grain number and quality (Surmaini et al., 2024). Warming temperatures and shifting isotherms have facilitated increased generation turnover and expanded migratory ranges of BPHs, notably promoting northward overwintering expansion in East Asia (OISHI et al., 2024). Abiotic stressors like temperature and humidity modulate insect population dynamics by influencing developmental rates, fecundity, survival, and migration potential (Sunil et al., 2023).

5.3 Maize

Maize (*Zea mays* L.), important crop as food and feed worldwide, grown on approximately 194 million hectares. As major cereal the increasing cultivation of maize in a rotation with wheat in the era of climatic extremes made it vulnerable to a range of biotic stresses (Pfordt and Paulus,2025). In sub-Saharan Africa, maize yield losses attributable to fall armyworm infestations are estimated to range between 8.3 and 20.6 million tons annually, corresponding to 21%–53% of total maize production across 12 major maize-producing countries (Lazutkaite et al., 2024).

5.3.1 Climate-driven outbreaks of fall armyworm and it's expanding dynamics

The fall armyworm (*Spodoptera frugiperda*), a highly destructive and invasive lepidopteran pest, has emerged as a serious global threat to maize production. While maize is its primary host, *S. frugiperda* poses a threat to over 80 plant species, including rice, sorghum, millet, sugarcane, cotton, and various vegetable crops, thus jeopardizing both food security and agricultural biodiversity (Lazutkaite et al., 2024).

Fall armyworm demonstrates high reproductive potential, capable of producing 4–6 generations per year in warmer climates. Its population surges during the warm and wet seasons—typically from March to October—are influenced by local climatic conditions, agricultural practices, and pest control availability (Guimapi et al., 2022; Niassy et al., 2021).

The pest is most damaging during the wet and post-rainy seasons and fails to establish viable populations where temperatures fall below 10 °C or exceed 40 °C. Suitability modeling has shown that *S. frugiperda*'s probability of occurrence increases linearly with precipitation above 3 mm in the driest month, but decreases when precipitation exceeds 100 mm in the coldest quarter (Karuppannasamy et al., 2024).

Temperature and humidity are the primary climatic variables governing the development, survival, and spread of FAW. The coldest annual temperature acts as a significant constraint on its year-round distribution while erratic precipitation patterns contribute to the creation of favorable breeding conditions (Niassy et al., 2021; Guimapi et al., 2022).

5.4 Barley and other cereals

5.4.1 The hessian fly, an emerging pest in cereals

The Hessian fly (*Mayetiola destructor*, Diptera: Cecidomyiidae) is one of the most economically significant insect pests affecting cereal crops such as wheat, barley, and rye. Although wheat remains its primary host, recent observations indicate that *M. destructor* is increasingly impacting barley production, underscoring the pest's adaptive capabilities and its potential to threaten broader cereal crop systems (Karki et al., 2024).

5.4.2 Aphids: Molecular interactions and pest dynamics

Aphids represent another major group of insect pests in cereals, notable for their highly efficient colonization strategies and capacity to inflict both direct damage and act as vectors for plant viruses with remarkable reproductive capabilities (parthenogenesis), enabling rapid population expansion under favorable conditions. Aphids feed by inserting specialized mouthparts (stylets), concurrently delivering salivary effectors that manipulate host cell processes. These effectors can suppress plant defense responses, alter host metabolism, and facilitate aphid proliferation.

Advancements in molecular biology and omics technologies have significantly deepened our understanding of plant–aphid interactions, offering promising avenues for sustainable pest management. Aphid feeding activates these pathways, resulting in the synthesis of secondary metabolites and signaling cascades that deter further infestation. Studies involving cereal aphids such as *Sitobion avenae*, *Schizaphis graminum*, and *Rhopalosiphum padi* have shown that aphid infestation alters plant amino acid profiles and activates specific defense genes (Kumaraswamy and Huang, 2024). Moreover, phloem sap contains lectins that bind to carbohydrate moieties in the aphid gut, disrupting physiological processes and impairing insect fitness.

5.4.3 Insect vectors and viral transmission in cereal crops

Many hemipteran insects, including aphids, whiteflies, leafhoppers, and thrips, are primary vectors of plant viruses. Environmental conditions significantly influence vector activity and virus epidemiology. Elevated temperatures enhance the reproductive rates and mobility of vector accelerating virus dissemination. Concurrently, drought stress weakens plant defenses and increases feeding frequency and duration facilitating virus acquisition and transmission (Yigezu and Kassaye, 2024).

Table 1: Case studies on climate change-driven insect dynamics in major cereal crops

Cereal Crop	Major Insect Pest(s)	Climate-Driven Dynamics	Plant Defense Mechanisms	References
Wheat	Hessian Fly (*Mayetiola destructor*), Aphids (*S. avenae*, *S. graminum*, *R. padi*)	Expanding host range due to rising temperatures; rapid aphid population growth with warmer climate and parthenogenesis	Secondary metabolites; phloem lectins; SA and JA signaling; plant–aphid interactions modulate amino acid levels	(Bajwa et al., 2020; Kumaraswamy and Huang, 2024; Tadesse et al., 2022)
Rice	Brown Planthopper (BPH), Rice Gall Midge, Yellow Stem Borer	Rising temperatures and humidity favor pest outbreaks and migration; drought and flood conditions affect pest establishment and rice phenology	JA and SA signaling pathways; production of terpenoids and phenolics	(Danso Ofori et al., 2025; Jasrotia et al., 2019;
Maize	Fall Armyworm (*Spodoptera frugiperda*)	Warmer, wetter conditions accelerate generation cycles; migratory behavior aided by wind; sensitive to temperature extremes (<10°C or >40°C)	Constitutive and induced defenses; jasmonic acid-mediated responses; emission of GLVs; TPS23 gene synthesizes (E)-β-caryophyllene to attract predators	(Abro et al., 2021; Guimapi et al., 2022; Karuppannasamy et al., 2024)
Barley	Aphids (vectors of BYDV), Hessian Fly	BYDV incidence rises with increased vector activity under warm and dry stress; virus transmission efficiency enhanced under drought	No complete immunity; *Ryd4Hb* gene confers resistance to BYDV (not vector); HvTHIC gene regulation affected by BYDV-GAV; thiamine and SA accumulation	(Fitzgerald et al., 2022; Han et al., 2024; Yigezu Wendimu and Kassaye Gurmu, 2024)
Other Cereals (Sorghum, Millet)	Fall Armyworm, Aphids, Thrips	Vulnerable to cross-species pest migration; precipitation >3mm in driest month favors FAW establishment	Defense varies by genotype; similar hormonal signaling and volatile emissions observed	(Hossain et al., 2022; Niassy et al., 2021; Phukon et al., 2023)

6. ADVANCED MOLECULAR INSIGHTS

Due to rapid pace of climate change it is very important to understand the molecular mechanisms behind insect adaptation, pest resistance and crop-insect-microbe interactions. Strong molecular tools are now complementing traditional ecological and physiological approaches. Recent developments in molecular biology that are influencing crop resilience to climate stress and insect pest management are highlighted in this section.

6.1 Role of transcriptomics in studying insect adaptation to climate change

Transcriptomics is the field of molecular biology focused on studying the transcriptome—the complete set of RNA transcripts (coding and non-coding) produced by the genome in a cell, tissue, or organism under specific conditions. A transcriptome provides the whole complement of RNA transcripts present in a cell at a specific time (Lowe et al., 2017). Transcriptome sequencing has emerged as an efficient tool in providing accurate information related to biological as well as evolutionary development of insects. Transcriptional studies have helped for dissecting the intricate gene regulation driving insect immune responses to pathogens (Sackton, 2019). The genetic basis of caste differentiation in social insects by cataloging genes and regulatory networks associated with distinct phenotypes, uncovering mechanisms underlying their specialized roles (Orr and Goodisman, 2023). There are many species which have narrow transcriptional plasticity which are less likely to survive environmental changes, as they cannot modify their physiology through gene regulation (Drury, 2020).

6.2 Genomic approaches to identify pest-resistant crop traits

6.2.2 Metagenomics

Metagenomics is the study of genetic material which is recovered directly from environmental or clinical samples and it is possible to analyze the collective genomes of microbial communities in their natural habitats. At present metagenomics can be a promising technique to find out pest resistant traits in cereal crops. Through shotgun sequencing and bioinformatics analyses it is possible to detect biosynthetic gene clusters and resistance-associated loci (Pérez-Cobas et al., 2020). If these microbial signatures are correlated with plant genotypes the overall process can find out natural biocontrol agents and symbiotic interactions which will be supportive to suppress pest insects. Besides, Microbes act as a prominent biocontrol agent for pest control as they can produce antagonistic molecules and influence plant defense mechanism through hormone production (Chaudhary et al., 2024a).

6.2.2 Marker-Assisted Selection and QTL Mapping

Marker-assisted selection allows breeders to select for pest resistance by tracking molecular markers linked to key resistance genes. MAS has been widely used in rice to incorporate genes conferring resistance to the brown planthopper (*Nilaparvata lugens*) (Hu et al., 2016). QTL mapping further enables the identification of genomic regions associated with insect resistance. Recent efforts have focused on stacking multiple QTLs to develop broad-spectrum and durable pest-resistant varieties (Wani et al., 2022).

6.3 Epigenetic modifications in insects under temperature and CO2 changes

6.3.1 DNA Methylation and Thermal Stress

Temperature variations can induce changes in DNA methylation patterns in insects that affects gene expression related to development, metabolism and stress responses. Studies have shown that exposure to elevated temperatures can lead to differential methylation in genes associated with heat shock proteins and metabolic pathways and it facilitates thermal tolerance (de Carvalho, 2023).

6.3.2 Histone Modifications and Gene Regulation

Histone modifications for example acetylation and methylation influence chromatin structure and gene accessibility. Environmental stressors shifts can alter histone modification patterns which leads to the activation or repression of genes involved in stress responses (Abdulraheem et al., 2024). These changes can be temporary or heritable which affect insect physiology and behavior throughout the generations.

6.3.3 Non-Coding RNAs and CO_2 Exposure

Non-coding RNAs which includes microRNAs (miRNAs) play a crucial role in post-transcriptional gene regulation. Elevated CO_2 levels have been linked to changes in miRNA expression profiles in insects and it impacts genes related to respiration, energy metabolism, and neural function. These alterations can affect insect behavior and adaptability to high CO_2 environments (Lee and Yun, 2023).

6.3.4 Transgenerational Epigenetic Inheritance

Emerging evidence suggests that epigenetic modifications induced by environmental stressors can be transmitted across generations and it influences offspring phenotypes. Insects exposed to temperature or CO_2 stressors have demonstrated heritable changes in gene expression and stress tolerance which indicates a mechanism for rapid adaptation to climate change (González-Tokman et al., 2022).

6.4 Molecular basis of symbiosis disruption

Microorganisms which utilize insects as hosts and established prolonged sustainable association with insects can be considered as insect symbionts. Microorganisms which colonize inside insects can promote certain positive effects on insects like insect fitness, protection against natural enemies and adverse condition (Lv et al., 2024). Moreover, several invasive stink bug (family Pentatomidae) shows obligate symbiotic association with bacteria belonging to family Enterobacteriaceae, seriously affects fitness and survival of newly hatched nymph for symbiont-containing secretions smeared by females fails to pass through digestive tract of nymphs, resulting prevention of orally acquiring symbionts (Gonella et al., 2020).

6.5 CRISPR and RNAi technologies for pest management under climate stress

CRISPR is widely used to enhance pest resistance in crops by targeting plant genes associated with susceptibility or modifying pathways linked to defense mechanisms. Targeted editing of susceptibility genes in rice and maize has resulted in increased resistance to stem borers and other chewing insects (Moon et al., 2022). RNA interference suppresses the expression of gene through double stranded RNA (dsRNA) with high degree of specificity. Here the silencing genes may be that specific gene which is essential to pest survival and reproduction. RNAi-based pesticides are developed following this mechanism and these pesticides can be applied incorporated into transgenic plants, facing challenges in effective delivery method. Recent advancements have focused on developing polymeric nanocarriers to protect dsRNA from degradation and increase uptake by pest tissues. It has been found that these nanocarriers enhance the stability and efficacy of RNAi-based treatments (Yang et al., 2022).

Table 2: Summary of advanced molecular mechanisms of controlling cereal pests in the era of climate change

Molecular Approach	Application in Cereal Crops	Climate-Driven Pest Dynamics	Plant/Insect Response Mechanisms	References
Transcriptomics	Identifies DEGs related to stress and immunity in insects; used to study transcriptional plasticity in pests of cereals	Temperature extremes, drought, and fluctuating climates drive genomic variation and insect stress response	DEGs in insects (e.g., HSPs, immune genes); identification of plasticity levels for prioritizing pest threats	(Drury, 2020; Sackton, 2019)
Metagenomics	Detects microbial signatures and biosynthetic gene clusters in rhizosphere of cereals like rice and maize	Microbiome shifts due to climate affect natural biocontrol potential	Identification of beneficial microbes linked to pest resistance; microbial hormones influence plant immunity	(Chaudhary et al., 2024a; Pérez-Cobas et al., 2020)
QTL Mapping	Used for breeding pest-resistant varieties in rice (BPH resistance), maize, etc.	Accelerated pest outbreaks under favorable climates increase need for durable resistance	QTL stacking; molecular markers linked to resistance genes allow rapid screening of climate-resilient varieties	(Hu et al., 2016; Wani et al., 2022)
Epigenetics	Studies gene expression regulation under climate stress in cereal pests	Elevated temperatures and CO_2 levels induce transgenerational changes in pests	DNA methylation (e.g., HSP genes), histone modifications, miRNA alterations impacting stress responses and metabolic processes	(Al Aboud et al., 2025; de Carvalho, 2023; González-Tokman et al., 2022; Lee and Yun, 2023)
Symbiosis Disruption	Targets obligate symbionts in pests (e.g., stink bugs on cereals) for pest control	Climate affects host–symbiont stability; disrupting symbioses impairs pest fitness	Symbiont deprivation through egg sterilization or environmental stress; manipulation of gut microbiome	(Gonella et al., 2020; Lv et al., 2024; Nikoh et al., 2014; Snyder and Rio, 2015)
CRISPR-Cas9	Genome editing in cereals (e.g., rice, maize) to improve pest resistance; gene drive strategies in insect pests	Helps develop climate-smart crops; gene editing targets pests adapting rapidly to warming climates	Editing susceptibility genes in plants; inducing sterility in pests like *Drosophila suzukii*	(Kaur et al., 2025; Moon et al., 2022)
RNAi (RNA interference)	Applied via transgenic plants or external sprays to silence pest genes in rice, maize, and wheat	Useful under unpredictable pest population surges due to climate variability	dsRNA delivery via nanocarriers; targets essential insect genes; specific and eco-friendly	(Finetti et al., 2023; Yang et al., 2022)

7. IPM IN THE ERA OF CLIMATE CHANGE

7.1 Advanced modeling of pest outbreaks using climate data

7.1.1 Phenology models

Phenology models have been successfully applied to predict the timing of critical insect life stages, predator-prey interactions and introduction, establishment and range expansion probabilities of invasive or introduced insect species as it provides accurate result (Rincon et al., 2024).

7.1.2 Matrix models

Recent advances in artificial intelligence (AI) technology have the potential to deal with many of these challenges; massive weather forecasting and imagery dataset can be collected worldwide and analyzed using deep-AI models (Ali et al., 2024). In recent years, imaging techniques and computer vision approaches in various electromagnetic spectrum areas have become increasingly important for identifying and classifying plant diseases.

7.2 Biological control strategies and their limitations under changing climates

7.2.1 Control strategies

Global climate change impacts biodiversity and ecosystem health through multiple, interrelated processes that involve habitat loss, agricultural intensification, invasive species, climate change, and chemical pollution. In more recent decades, biological control, a key component of IPM and an alternative to chemical pesticides, has also gained momentum beyond the agrifood sector i.e., in public health and environmental protection domains. It involves the use of natural enemies such as predators, parasitoids (macroorganisms), and pathogens (microorganisms) to manage pest populations.

7.2.2 Limitations

Biological control is a valuable and effective strategy for controlling arthropod pests for no doubt and has been used extensively against invasive arthropods. But scientists began raising significant concerns and

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questions about non-target and indirect effects that can be caused by these introductions. In recent years, similar issues have been raised about augmentative use of exotic natural enemies where, introduced exotic species can also attack native species.

7.3 Genetically engineered biocontrol agents

Microbes used in bio-pesticide formulations (which may or may not be genetically engineered) are pest-specific so that they do not target non-pest species. Moreover, they are highly selective, less toxic, and their pesticidal action is either due to the microbe itself or by toxin production. These extensively used microbial pesticides consist of bio-insecticides (Bt), bio-fungicides (*Bacillus* sp., *Pseudomonas* sp., *Trichoderma* sp.), and bio-herbicides (*Phytophthora* sp.) (Chaudhary et al., 2024a). Entomopathogenic fungi (EPF), notably hypocrealean ascomycetes, stand out among microbial pesticides because of their unique mode of action through the cuticle. This attribute grants them a notable edge in integrated pest management approaches (Qin et al., 2023).

Bacterial species employed as biological control agents are categorized as facultative pathogens (P. aeruginosa), obligate pathogens (B. popilliae), crystalliferous spore formers (B. thuringiensis) and potential pathogens (Serratia marcescens), while spore-forming have broad applications because of their effectiveness, safety and specificity (Chaudhary et al., 2024b). Bt produces insecticidal proteins during the sporulation phase as parasporal crystals, predominantly comprised of one or more proteins (Cry and Cyt toxins) viewed as highly safe, specific, and sustainable alternatives to conventional pesticides for pest management (Bravo et al., 2007; Chaudhary et al., 2024a).

Entomopathogenic viruses that develop granular bodies and polyhedral bodies inside the host cells, not only crucial to pest management but also poses no detrimental effects on both humans and animals. Bio-pesticides have the significant benefit of overcoming the increased resistance in pests (Chaudhary et al., 2024b). Entomopathogenic nematodes (EPNs) are biocontrol agents that are used to control a wide variety of insect pests within agriculture and forestry. In addition to their use as bio-pesticides, EPNs have a fascinating biology and are thus considered model organisms in ecology, symbiosis and pathogenesis (Shapiro-llan and Lewis, 2024). Nematodes and their symbiotic bacteria have been tested against some species of hemipterans, including stink bugs, and have shown promising results, with significant insect mortality rates (Esparza-Mora et al., 2024).

Table 3: Genetically engineered and microbial biocontrol agents used against insect pests in cereal systems

Biocontrol Agent	Target Pest/Group	Mechanism of Action	Advantages	References
Bacillus thuringiensis (Bt)	Lepidopteran pests (e.g., stem borers, leaf folders)	Produces δ-endotoxins (Cry and Cyt proteins) that disrupt insect gut; specific ingestion-based toxicity	Highly specific, sustainable, widely used in transgenic crops; 90% of U.S. bio-pesticide products	(Bravo et al., 2007; Chaudhary et al., 2024a)
Metarhizium and *Beauveria* spp.	Lepidopterans and other insects	Fungal spores adhere to and penetrate cuticle, proliferate in hemocoel, causing death via toxins or tissue invasion	Broad host range; independent of ingestion; suited to IPM	(Karthi et al., 2024; Zhou et al., 2024a)
Bacterial agents (*B. subtilis*, *P. aeruginosa*, *B. popilliae*, *S. marcescens*)	Insect pests and plant pathogens	Toxin production, competitive exclusion, endophytic colonization	Specificity, cost-effective, some strains are GRAS (e.g., *B. subtilis*)	(Chaudhary et al., 2024b)
Entomogenous viruses (Granulosis and Polyhedrosis viruses)	Host-specific lepidopterans and other pests	Viral infection leading to host death via cell destruction and inclusion body formation	Host-specific, environmentally safe alternative to chemical pesticides	(Chaudhary et al., 2024b)
Entomopathogenic nematodes (EPNs) + symbiotic bacteria	Hemipterans (e.g., stink bugs), other soil-dwelling pests	Infect through natural openings; symbiotic bacteria cause septicemia and death	Model organisms in ecology; effective, eco-friendly control agents	(Shapiro-llan and Lewis, 2024) (Chaudhary et al., 2024b)

7.4 Sustainable pest management approaches in cereal systems

Sustainable pest control practices, within an IPM framework, are important for addressing the challenges posed by the increasing global demand for food, the necessity to conserve national bioresources, and the urgency to mitigate the adverse effects of climate change. By curtailing overall chemical pesticide reliance, IPM fosters biodiversity conservation, safeguards ecosystem services, and strengthens the stability of agricultural systems. Furthermore, the utilization of IPM procedures can yield economic benefits for farmers through reduced input costs and enhanced crop yields, whereas simultaneously promoting food safety and produce quality for consumers.

The pressing necessity to develop more sustainable and robust agricultural frameworks in the light of mounting global challenges, the widespread embracing of IPM practices is essential. Scouting and sampling techniques are fundamental components of the monitoring and decision-making process in IPM programs. Remote sensing techniques, such as aerial photography, satellite imagery, and unmanned aerial vehicles (UAVs), are increasingly being used to monitor crop health and detect pest outbreaks over large spatial scales (Zhou et al., 2024b).

7.4.1 The push–pull strategy

Push-Pull Technology (PPT) is one method which has been very effective in farmers' fields as a sustainable agricultural intensification practice (SAIP) and an integrated pest management system (IPM) helping to avert the negative effects of pesticide application. The push–pull effect is established by exploiting semiochemicals including pheromones to repel insect pests from the crop ('push') and to attract them into trap crops ('pull') (Hassanali et al., 2008).

7.4.2 Acceleration of sustainable intensification

The impacts of climate change, particularly extreme weather events, will increase the likelihood of crop failure in the future. As such, the need for the development of climate-resilient crops that increase agricultural efficiency and sustainable land use is critical to food security. Conservation agriculture, including practices such as reduced tillage, continuous cover, and crop rotation, provides a foundation for safeguarding agricultural systems. To support the widespread adoption of these practices, it will be necessary to make technological advancements through machinery breakthroughs, automation, advanced genetics, and biotechnology. Climate change is driving the need for adaptation and resilience in agriculture.

Through factor analysis, the primary advantages and disadvantages of utilizing IPM in farm field were categorized into six factors, namely: low efficacy in pest control, personal drawbacks, weak technical and support services (as disadvantages of IPM), as well as health benefits, cost effectiveness, and social advantages (as advantages of IPM) (Abdollahzadeh and Sharifzadeh, 2024).

8. FUTURE PERSPECTIVES AND CHALLENGES

8.1 Integration of advanced molecular tools with field management strategies

The transition to advanced molecular techniques has become a game-changer in overcoming the challenges of crop quality improvement. Traditional breeding methods have faced numerous challenges, such as long breeding cycles, low genetic diversity, and unpredictable outcomes. This has significantly reduced the time and resources required to develop new crop varieties with improved yield, disease resistance, and nutritional value. Advanced molecular techniques for addressing malnutrition and improving human health as bio fortification (Khan et al., 2024).

8.1.1 Marker-Assisted Selection (MAS)

MAS has been successfully applied to improve crop yield-related traits in several crops. These markers are typically used to track the inheritance of specific traits or genes of interest in breeding programs, genetic mapping, and population studies detecting genetic variations at the molecular level, these markers provide valuable insights into genetic diversity, evolutionary relationships, and trait inheritance patterns across different organisms (Sai Tharun et al., 2024).

For example, in rice, MAS has been used to identify and select plants with high yield potential, disease resistance, and drought tolerance. In maize, MAS has been used to develop hybrids with high yield potential, improved grain quality, and resistance to pests and diseases. In wheat, MAS has been used to select plants with high yield potential, drought tolerance, and disease resistance (Khan et al., 2024).

8.1.2 Genomic Selection (GS)

Genomic Selection (GS) is a molecular breeding technique that involves selecting superior individuals for breeding based on their genomic information. For example, in maize breeding, GS has been used to develop hybrids with high yield potential, improved grain quality, and resistance to pests and diseases (Hasan et al., 2025).

8.2 Policy and global cooperation in mitigating climate impacts on agriculture

The intersection between climate change and agriculture -especially cereals food safety presents complex challenges that demand urgent attention and effective policy responses. Extreme weather events pose risks to crop health, soil fertility, and overall agricultural productivity. By analyzing climate data alongside food safety data, authorities can identify vulnerable regions, prioritize resources, and implement targeted interventions to mitigate risks. Early warning systems utilize real-time data and predictive analytics to identify potential risks and trigger proactive interventions to prevent foodborne illness outbreaks. Policymakers can support crop diversification by promoting the cultivation of climate-resilient crop varieties, intercropping and crop rotation practices, and providing financial incentives for farmers to diversify their production systems that are essential for enhancing awareness empowering stakeholders with the knowledge and skills needed to prevent, detect, and mitigate foodborne hazards, particularly in the context of climate change (Michael Alurame Eruaga, 2024b).

Governments worldwide have recognized bioenergy's potential from wheat, maize, barley to mitigate climate change, enhance energy security, and promote rural development. As a result, numerous policy instruments have been implemented to incentivize bioenergy production and consumption. The Paris Agreement, a landmark in international climate policy, serves as a foundation for such strategies, yet its implementation varies considerably across nations. Community engagement in policy development is emphasized as a crucial element for the success of climate strategies, aligning with the principle that local and indigenous knowledge is vital for effective adaptation (Gutwa Oino and Musau, 2024). Comparative analyses of global case studies shed light on the diverse nature of policy effectiveness across different contexts, providing a broader perspective on adaptation strategies.

8.3 Ethical considerations in molecular and genetic interventions

According to Welfare Councils in The Netherlands and the UK defined “five freedoms”: Freedom from hunger and thirst; Freedom from discomfort; Freedom from pain, injury, and disease; Freedom to express natural behavior; Freedom from fear and distress. In light of these rights, various ethical dilemmas different advanced technologies are more than important. Parallel analyses are possible in relation to plant breeding. Lammerts van Bueren and Struik arrive at the following rights of crop plants from their organic/biodynamic point of view: plant has the integrity of life, plant has the right to follow its biorhythms, genotypic integrity to co-evolve with human development, consistent phenotypic integrity with the nature of the plant and human intentions (Louwaars and Jochemsen, 2021).

The ethical considerations associated with genome editing in maize and other crops revolve around issues like unintended off-target effects, ecological impacts, and equitable access to advanced technologies. Balancing the potential benefits of genome editing with regulatory compliance and ethical considerations is a challenge that must be addressed as agriculture continues to embrace these cutting-edge technologies (Singh et al., 2024). While advanced molecular approaches like CRISPR-Cas9, transgenesis offer certain limitations that need to be considered: The use of advanced molecular techniques, such as genome editing, raises ethical and regulatory concerns. Some advanced molecular techniques can be expensive and require specialized equipment and expertise. This may limit their accessibility, particularly for small-scale farmers or researchers in resource-constrained settings. Efforts are being made to make these technologies more affordable and accessible to a wider range of users.

9. CONCLUSION

Climate change is catalyzing a complex and often nonlinear transformation of insect pest dynamics across global agricultural landscapes. The acceleration of pest development rates, expansion into new habitats, and disruption of trophic interactions collectively challenge the sustainability of current pest management approaches. As climatic extremes intensify, the risk of pest outbreaks and crop losses escalates, particularly in vulnerable smallholder systems. Addressing these challenges demands an urgent reorientation of pest management paradigms—one that incorporates robust climate-pest modelling, adaptive surveillance, breeding for pest-resilient cultivars, and ecosystem-based solutions. A transdisciplinary approach, bridging entomology, climatology, agronomy, and data science, will be essential to develop resilient agroecosystems. The future of sustainable agriculture hinges on our ability to anticipate and adapt to the pest-related consequences of climate change with precision, agility, and ecological sensitivity.

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