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Host Plant Resistance under Changing Climatic Scenario: Improvement and Exploration for Climate Smart Pest Management

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Abstract

Climate change presents a widespread issue that impacts the dynamic between pests and crops on a global scale. Rising temperatures, increased CO_2 levels, and alterations in rainfall patterns are influencing the distribution, population, and potential damage of insects worldwide. The excessive use of pesticides is resulting in significant adverse effects on both the environment and human health. Furthermore, the production of fumigants is closely linked to the exacerbation of global warming. In the face of changing climatic conditions, plants' natural defenses against pests are being disrupted. It is imperative to develop resilient crop varieties that can withstand these changes and maintain resistance against pests. Additionally, there should be a greater emphasis on utilizing host plant resistance to ensure sustainability in agricultural practices.

Introduction

The effects of climate change are clear and observable. Since the late 19th century, both Global Mean Surface Temperature (GMST) and atmospheric CO_2 concentrations have been rising rapidly. Projections indicate that by 2100, temperatures could increase by 1.4 to 5.8 degrees Celsius, accompanied by a CO_2 increase of around 40% compared to preindustrial levels. By the century's end, atmospheric CO_2 levels could reach between 500 and 1000 parts per million (ppm) (Anonymous, 2014). Climate change is a worldwide occurrence with widespread consequences, particularly impacting developing nations like India. Elevated levels of carbon dioxide and rising temperatures have significant implications for the agricultural sector, affecting both crops and herbivorous insect pests. The global atmospheric concentration of carbon dioxide continues to escalate swiftly, primarily due to the combustion of fossil fuels. Since the preindustrial era, atmospheric CO_2 levels have surged from 270 ppm to the current 394 ppm, marking a 124 ppm increase or a 45% rise (Global Carbon Budget.org). Most studies forecast that CO_2 levels will double from preindustrial levels within the next

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five to ten decades. This escalation represents one of the most extensive and far-reaching disruptions to the environment (Anonymous, 2014). In the last two decades, numerous researchers worldwide have contributed to a collective comprehension of the direct impacts of rising CO_2 levels on plant growth and functionality. Conversely, the effects of elevated CO_2 on insects are predominantly observed to be indirect (Murray et al., 2013). Given that climate directly influences agricultural production, it's natural for the research focus to gravitate towards the agricultural sector. These alterations directly influence the growth and maturation of crop plants. It's anticipated that environmental shifts will have adverse effects, impacting both plant and insect populations. Herbivorous insects, as primary consumers deriving energy from plants or plant-based products, are particularly vulnerable. The repercussions of climate change on these insects could have profound effects on ecosystem dynamics and potentially lead to significant alterations (Cornelissen, 2011). Increasing temperatures, heat stress, and changes in precipitation patterns are causing a decline in crop resilience. For instance, drought conditions diminish the natural defenses of plants and alter their biology, rendering them more susceptible to pests. Elevated temperatures are expected to likely accelerate the growth of insect populations in specific areas. Additionally, scientists anticipate ongoing changes in the geographic distribution of insects and their ability to survive through winter. Due to climate change several pests are extending their potential to thrive in well adapted manners, with a higher capacity to damage the crops. Climate change accelerates the degradation of pesticides, resulting in reduced effectiveness over time. This prompts farmers to increase their pesticide application rates. Due to farmers' limited capacity to invest in plant protection measures, pest and disease occurrences frequently result in significant losses of productivity and income. Therefore, there is substantial potential to establish a more diverse and resilient system less susceptible to pests and diseases (Risch, 1983). The domestication of agricultural crops, which encompasses around 2500 species worldwide according to Meyer *et al.* (2012), has entailed the artificial selection of favorable traits that improve both yield and the quality of harvested products. Breeding for agronomic goals in high-input environments has effectively boosted global crop productivity (Lynch, 2007). The decrease in genetic diversity may restrict the availability of crop varieties suited for cultivation under less-than-ideal conditions. Plant defensive traits might be deficient or expressed weakly in domesticated plants due to the prioritization of other desirable traits during selection (Chen et al., 2015). In all types of vegetation systems, herbivores that feed on foliage, sap, and roots collectively reduce more than 20% of net plant productivity (Agrawal, 2011). Despite the escalation in pesticide usage in recent years, these losses persist, underscoring the necessity for the development of sustainable pest control methods that reduce dependence on chemical inputs. In order to mitigate concerns regarding human health, environmental safety, and pesticide resistance, it is imperative to utilize plant defensive traits more extensively in crop protection strategies.

Pesticides and climate change

Warmer temperatures bring favorable conditions for insect pests as well. Monocropping ensures a constant food source, and the warmer climate is predicted to prolong their feeding period. With milder winters, insect mortality rates are expected to decrease, leading to an expansion of pest territories into northern regions. Taken together, these factors suggest a potential increase in chemical pesticide usage, or an opportunity for a significant shift in agricultural practices towards prioritizing soil health and reducing emissions. A report by the Intergovernmental Panel on Climate Change indicates that approximately 30% of global emissions contributing to climate change stem from agricultural activities, which include the use of pesticides (Anonymous, 2016). According to researchers at the Pesticide Action Network North America (PANNA), pesticides play a significant role in contributing to climate change. The relationship between pesticides and climate change forms a cycle: Pesticides contribute emissions to the atmosphere, which accelerate climate change. As climates warm, agricultural systems come under stress, leading to a rise in pests and insects, necessitating increased pesticide usage (Rose, 2023). Only a limited number of studies assess the greenhouse gas (GHG) emissions from pesticide use throughout its entire life cycle, encompassing production, storage, transportation, application, and breakdown. During the production of pesticides, three primary greenhouse gases are released: carbon dioxide, methane, and nitrous oxide (Heimpel et al., 2013). Regarding production, the majority 99% of synthetic chemicals, including pesticides, originate from fossil fuels. However, they receive less attention compared to nitrogen fertilizer, another crucial agricultural input associated with high GHG emissions. Research indicates that the production of one kilogram of pesticide typically demands approximately ten times more energy than producing one kilogram of nitrogen fertilizer. Pesticides may emit greenhouse gas (GHG) emissions even after their application. Fumigant pesticides, in particular, have been demonstrated to notably elevate nitrous oxide production in soils, a greenhouse gas 300 times more potent than carbon dioxide. Additionally, numerous pesticides contribute to the generation of ground-level ozone. Studies conducted in the USA have demonstrated that commonly utilized soil fumigants like chloropicrin can amplify soil N_2O emissions by seven times, with their impacts persisting significantly longer than emissions induced by fertilizers. Certain pesticides, such as sulfuryl fluoride, which is applied to insects like termites and beetles, also act as greenhouse gases. Emitting one ton of sulfuryl fluoride has the same impact as releasing nearly 5,000 tons of CO_2. Additionally, researchers note that oil and gas companies exacerbate this problem and benefit from it, as 99 percent of synthetic pesticides are derived from petroleum (Rose, 2023). Addressing climate change necessitates a broad transition from pesticide-centric agriculture to agroecology. This shift will foster resilient, regenerative farming systems that emit fewer greenhouse gases, enhance biodiversity, and yield fair returns for farmers. Moreover, agroecological farming systems inherently possess greater resilience and can better withstand climate shocks such as extreme flooding and drought. In this context host plant resistance may address the above issues.

Host – insect interaction under elevated CO_2

The levels of atmospheric CO_2 have risen by more than 20%, impacting plant growth and various physical and chemical attributes of plants and crops. These alterations involve decreased leaf nitrogen, shifts in defense compounds, water content, carbohydrates, and leaf thickness. It is suggested that heightened CO_2 exposure will enhance plant photosynthesis, growth, above-ground biomass, leaf area, yield, carbon content, and the carbon-to-nitrogen ratio. Such modifications can affect the nutritional quality of plant-based food for herbivorous insects (Hunter, 2001). The chemical makeup of certain plant species undergoes alterations due to biotic and abiotic stresses. Consequently, their tissues become less conducive to the growth and survival of insect pests (Sharma et al., 2002). Higher levels of carbon dioxide (CO_2) typically result in the buildup of carbohydrates in plant leaf tissue due to heightened rates of photosynthesis, leading to an augmentation in the carbon to nitrogen ratio of leaves. As nitrogen (N) is regarded as a nutrient that often restricts insect growth, the decrease in N concentration resulting from this dilution diminishes the nutritional value of the leaves. Moreover, alterations in plant chemical defenses have been observed in response to elevated CO_2, potentially exerting additional effects on the performance of herbivores (Robinson et al., 2012). Changes in insect-plant interactions will occur as a result of CO_2's impact on the nutritional value and secondary compounds of host plants. Elevated CO_2 levels will boost plant growth but could also amplify the harm inflicted by certain herbivore insects (Gregory et al., 2009). Under conditions of elevated CO_2, insects encounter less nourishing host plants, potentially leading to prolonged larval developmental periods. Elevated CO_2 levels might also result in a minor reduction in nitrogen-based defenses like alkaloids, alongside a slight rise in carbon-based defenses such as tannins (Lindroth, 1996). Effects of heightened CO_2 on insect pests indicated a widespread decline in foliar nitrogen levels and an uptick in carbohydrate and phenolic (secondary) metabolites. Herbivore consumption was mainly associated with shifts in nitrogen and carbohydrate levels. As herbivores experience impacts, higher trophic level organisms, such as secondary consumers, are also affected. While there is improving understanding of the effects of elevated CO_2 on interactions between individual herbivore species and their host plants, there is limited knowledge about how these effects might extend to secondary consumers, such as predators and parasitoids, thereby influencing entire food webs. Atmospheric CO_2 levels could directly or indirectly influence the performance of natural enemies and the susceptibility of prey (Lynch, 2007). Prasannakumar et al. (2012) investigated the impact of elevated CO_2 on BPH population in OTCs. They found that despite the beneficial effects of elevated CO_2 on rice crops, losses induced by BPH were higher under these conditions due to increased pest population and feeding rates.

Host – insect interaction under elevated temperature

The phenomenon of climate change, leading to rising temperatures, could intricately affect insect pest populations infesting agricultural crops. Elevated temperatures have the potential to influence insect survival, growth, geographical distribution, and population abundance (Bale *et al.*, 2002). Temperature can directly affect insect physiology and development, or it can have an indirect impact through the physiology or presence of their hosts. There is evidence indicating that insect development rates are accelerating under climate change, leading to an increase in the number of generations per year (voltinism). This accelerated development results in higher rates of insect food consumption and may hasten the evolution of resistance to pesticides and to climate change (IPCC, 2014). Elevated temperatures will speed up the development of various insect species, including the cabbage maggot, onion maggot, European corn borer, and Colorado potato beetle. This could potentially result in the occurrence of more generations per year, leading to increased crop damage (Bale et al., 2002; Srinivasa Rao et al., 2009). The impact of rising temperatures on the number of insect generations is well-documented, particularly pronounced in temperate climates and to some degree in tropical regions. As surface temperatures rise, insect species tend to produce more generations, with shorter generation times. Phenology-based models for various insect pests suggest that increased temperatures in future climate scenarios could lead to the occurrence of additional generations (Kiritani, 2006). Recent research conducted by authors examining pest predictions under climate change scenarios revealed that *Spodoptera litura* on groundnut (Srinivasa Rao et al., 2015) and *Helicoverpa armigera* on pigeonpea (Srinivasa Rao et al., 2016) were projected to experience two to three additional generations during distant and very distant future climate change periods. This phenomenon was attributed to increased temperatures across the majority of locations in India. Historical trends indicate that both the diversity of insect species and the intensity of their feeding have augmented alongside rising temperatures. Variations in temperature induce phytochemical and morphological alterations in host plants. For instance, when subjected to nighttime temperatures of 17°C, tomatoes exhibit notably elevated concentrations of catecholic phenolics like chlorogenic acid and rutin compared to other temperature conditions (Bradfield and Stamp, 2004) which induces the resistance against insect pest. At 35°C, tomatoes exhibit reduced activity of polyphenol oxidase (PPO) and peroxidase (POX) (Rivero et al., 2003). Additionally, it has been observed that there is a significant decline in protease inhibitor activity in tomatoes when temperatures fall below 22°C (Green and Ryan, 1973). Under increased temperatures, there is typically an increase in the thickness of leaf trichomes (Bickford, 2016). In alfalfa (*Medicago sativa*), higher temperatures led to increased concentrations of plant secondary metabolites such as sapogenins and saponins, which suppressed the growth of caterpillars (*Spodoptera exigua*). Conversely, the green-veined butterfly, *Pieris napi*, responded to warming-induced lower-quality foliage in Brassicaceae by consuming significantly larger quantities of plant tissue (Bauerfeind & Fischer, 2013)

Resistance in plant against herbivory

The relationships between herbivorous arthropods and their plant hosts are intricate and have multiple dimensions. The general process through which a herbivore interacts with a plant typically includes several stages: an initial searching phase where the herbivore moves, often guided by visual and olfactory cues, from an area lacking a host-plant to a potential host; a contact evaluation phase influenced by various visual, physical, and chemical signals from the plant; and a host utilization phase during which the herbivore's performance is affected by a combination of nutrients, toxins, digestibility reducers, and other plant factors. Plant resistance arises from the manifestation of resistance-related traits by the plant, which influences various aspects of the herbivore's interaction with the host plant and other plant-associated organisms. Plant resistance can be described as the collective expression of genetically inherited traits that dictate the extent of damage (yield loss) inflicted on the plant by the herbivore (Painter, 1951; Smith & Clement, 2012). The process of identifying resistant genotypes often involves research aimed at categorizing them into one or more of three resistance categories initially outlined by Painter (1951). The initial category, known as 'antibiosis,' characterizes the adverse impacts of resistant plants on herbivore physiology and life history, resulting in reduced growth, survival, and fecundity. The second category, termed 'antixenosis' (originally labeled 'non-preference' by Painter but later renamed by Kogan and Ortman in 1978), describes plant traits that influence herbivore behavior, diminishing their preference for or acceptance of a plant as a host. Lastly, 'tolerance' refers to a plant's capability to endure herbivore injury, leading to reduced agronomic yields or quality to a lesser degree compared to a less tolerant plant under equivalent injury. The genotype of the crop exerts the most significant influence on the crop-pest interaction by modulating the expression of resistance-related traits. Therefore, crop genotype serves as the fundamental basis upon which management strategies are constructed. Utilizing plant resistance as a strategy offers numerous advantages compared to other pest management approaches. The impacts of plant resistance on the targeted pest are typically consistent and accumulative. Moreover, implementing plant resistance is often straightforward and cost-effective for farmers once the resistant variety is available. Furthermore, plant resistance generally harmonizes well with other tactics, such as insecticide applications and biological control. One of the most critical points is that plant resistance avoids the negative environmental impacts associated with insecticide application. Moreover, utilizing resistant plant varieties can result in decreased insecticide usage (Wilde, 2002; Wiseman, 1994).

Need for breeding for pest resistance amidst changing climatic scenarios

Developing climate-resilient crops is crucial for safeguarding food security amidst growing climate-related challenges. This section examines different breeding strategies, encompassing traditional methods, molecular breeding techniques, and genomic and transgenic approaches, which have demonstrated potential in improving crop tolerance to both abiotic and biotic stresses. Climate change could potentially change the dynamics of interactions between insect pests and their host plants. Climate change can directly impact interactions between insects and plants, influencing the behavior and function of both insect pests and plants. Additionally, climate change can affect the development of secondary metabolites and other phytochemicals in plants. Climate change may exacerbate the impact of pests by exploiting reduced host defenses resulting from stress caused by inadequate adaptation to suboptimal climate conditions. Additionally, climate change could favor non-resistant crops or cultivars, leading to increased infestation by insect pests (Lobell & Gourdji, 2012). Climate change diminishes the defense mechanisms of plants against insect pests, making them more vulnerable to attack. For instance, early infestation of *H. armigera* in cotton and pulses has been observed in Northern India as a result (Sharma, 2014). Increased temperature might lead to the breakdown of temperature-sensitive resistance to particular insect pests. The loss of temperature-sensitive resistance in elevated temperature conditions could accelerate the evolution of pest biotypes. Sorghum varieties that previously showed resistance to sorghum midge, *Stenodiplosis sorghicola* (Coq.) in India, became vulnerable to the pest under conditions of high humidity and moderate temperatures in Africa. Due to global warming and heightened water stress, tropical nations such as India could encounter increased yield losses in sorghum due to the loss of resistance against the midge and spotted stem borer *Chilo partellus* Swinhoe (Sharma *et al.*, 2010). During colder winters, rapeseed-mustard crops are predominantly infested by *Lipaphis erysimi* and during milder winters, by *Myzus persicae*. As temperatures increase, we may observe a higher occurrence of *Myzus persicae*. Similar shifts in fauna may also occur in other crops. Additionally, climate change can influence interactions between pests and their natural enemies (Chander & Phadke, 1994). Temperature can impact the resistance of plants to viruses or insects. For instance, certain virus-resistant genes in wheat may lose their effectiveness under elevated temperatures, such as 18°C. Similarly, two insect-resistant varieties (IR26 and IR36), which each carried a single BPH-resistant gene, lost their resistance as temperatures rose to 31°C (Fahim et al., 2012; Wang et al., 2010). It has been observed that elevated CO_2 levels diminish plant defenses against insect pests. For instance, in soybeans exposed to increased CO_2 levels, the plant defense pathway signaling mediated by jasmonic acid (JA) is impaired (Zavala et al., 2008). Plants become vulnerable to insect pests such as the Japanese beetle, *Popillia japonica*, and the western corn rootworm, *Diabrotica virgifera*, due to decreased production of defensive cysteine proteinase inhibitors (CystPIs). Furthermore, higher temperatures and increased CO_2 levels influence the production of herbivore-induced plant volatiles (HIPVs) (Gouinguené & Turlings, 2002). Increased levels of CO_2 result in larger plant size and denser canopies, accompanied by foliage of superior nutritional quality and a microclimate that favors pests. With elevated CO_2, there is a rise in the carbon-to-nitrogen (C: N) ratio of plant foliage, prompting herbivores to increase feeding to acquire more amino acids. Rao et al. (2014) observed a higher C: N ratio in peanut foliage grown under elevated CO_2 compared to ambient levels, suggesting a potential increase in pest incidence in the future. Furthermore, elevated CO_2 positively influences the proliferation of BPH, leading to a population increase of more than double compared to ambient CO_2 levels. Additionally, honeydew excretion is elevated under elevated CO_2 conditions (Prasannakumar et al., 2012). Elevated CO_2 exposure suppresses the activity of jasmonic acid (JA), a plant defense hormone, while promoting the production of salicylic acid (SA). This leads to heightened susceptibility to chewing insects. To bolster the resilience of our crops against the impacts of climate change, selection goals must account for heightened variability in the production environment. This involves addressing the effects of more unpredictable rainfall and temperatures, including extreme weather events, as well as shifts in pest and pathogen distribution, leading to an increased likelihood of significant pest and disease outbreaks, along with the emergence of new pathogens. Farmers mitigate the inevitable risks associated with crop cultivation by choosing varieties that yield well and maintain quality under optimal conditions while minimizing losses during unfavorable seasons. Breeders and agronomists collaborate to assist farmers in specific target environments, but the increased variability of climate necessitates expanding the adaptability of cultivated varieties and enhancing yield stability to mitigate climate-induced risks and foster resilience (Langridge et al., 2021). Choosing to plant insect-resistant varieties rather than relying on widespread pesticide use is a more environmentally sustainable approach. However, to ensure the continued effectiveness of these insect-resistant varieties, it's crucial to consider the impact of climate change on them. The efficacy of insect-resistant genes hinges on whether they can maintain their resistance traits under changing climate conditions. Without this assurance, the misuse of insect-resistant genes could lead not only to no improvements in crop production but also to the potential loss of resistance altogether. Climate change may impact BPH resistance genes. NIL-BPH17 exhibits robust inhibition of BPH feeding on phloem and remains unaffected by environmental changes, whereas NIL-BPH20 may lose its efficacy under such conditions (Kuang et al., 2021). To mitigate the effects of climate and other environmental changes, it will be essential to develop new varieties with enhanced resistance to both abiotic and biotic stresses. Given the possibility of delayed onset or shortened duration of winter, there is a risk of delaying and shortening the growing seasons for certain *rabi* or cold season crops. Therefore, it is important to focus on breeding varieties that are suitable for late planting and capable of withstanding adverse climatic conditions, as well as pest and disease pressures.

Enhancing utilization of HPR for climate smart integrated pest management (CSIPM)

Climate-smart agriculture (CSA) is a concept coined by the Food and Agriculture Organization of the United Nations (FAO, 2010) to depict an innovative farming methodology aimed at guaranteeing food security. It involves implementing measures that steer agricultural systems towards sustainable development, fostering resilient practices, and adopting adaptable strategies in response to climate fluctuations. A crucial element of the CSA strategy involves the implementation of climate-smart pest management (CSPM), which offers numerous benefits in maintaining agricultural systems while reducing reliance on chemicals. Nonetheless, CSPM does have its constraints. Thus, this examination concentrates on elucidating the concept of CSPM and phytosanitary challenges linked to climate change, pinpointing areas that demand more effective interventions. Additionally, it delves into the prospect of adjusting pest management practices to align with weather patterns, aiming to bolster the sustainable evolution of agricultural systems. Heeb et al. (2019) recently crafted a thorough explanation of the CSPM concept. Sekabira et al. (2022), on the other hand, asserted that for climate-smart agriculture to be truly effective, it should adhere to climate-smart integrated pest management (CS-IPM). Consequently, they adopted the term CS-IPM to emphasize this integrated approach. The CS-IPM, or CSPM for short, represents a modernized iteration of the traditional integrated pest management concept, tailored to address the challenges posed by climate change. It employs intelligent methods to achieve sustainability objectives. Consequently, CSPM integrates various interdisciplinary approaches and strategies crucial for primary production to adapt to evolving climatic conditions. It emphasizes the synchronization of understanding pest biology with the implementation of cost-effective and efficient control techniques to mitigate harm to both humans and the environment.

Achieving a higher level of efficacy in utilizing host-plant resistance within integrated pest management (IPM) demands a deeper comprehension of the mechanisms governing plant resistance. This entails a thorough understanding of both the phenotypic and causal aspects of resistance. The biochemical and morphological characteristics responsible for plant resistance do not consistently manifest across plants in spatial or temporal dimensions. As a result, plant resistance influences both the distribution and population levels of herbivores. For instance, soybean aphids (*Aphis glycines* Matsumura) exhibited varied distribution patterns on the unifoliate leaves and shoot structures of different soybean lines exhibiting varying degrees of resistance. A thorough examination of the biochemical and morphological alterations linked to both inherent and stimulated plant resistance could aid in the creation of resistant plant varieties through conventional breeding techniques. Stimulated resistance typically exhibits a wide-ranging effectiveness, potentially shedding light on plant characteristics that offer broad-spectrum resistance. Furthermore, in-depth comprehension of plant resistance mechanisms might identify phenotypic traits that serve as substitutes for the labor-intensive and occasionally damaging task of quantifying resistance during the breeding phase. A deeper comprehension of the mechanistic foundations of plant resistance could propose innovative objectives and applications of genetic engineering. For instance, there's been discussion about altering plant terpene emissions to enhance their attractiveness to natural predators. Additionally, the potential transfer of R genes (genes conferring resistance) from one plant variety to another (such as from a less productive line to a superior cultivar) or even between different plant species (like among various cereal species) may become feasible in the foreseeable future as more insect-resistant genes are pinpointed. Another promising strategy involves combining natural plant resistance with transgenic resistance, commonly referred to as "pyramiding." For instance, incorporating a cystatin gene into potato plants with limited natural resistance to nematodes led to complete resistance, as demonstrated by Urwin et al. (2003). Similarly, a comparable approach of integrating natural and transgenic resistance has been proposed for controlling lepidopteran pests in soybean, as outlined by Zhu et al. (2008). Utilizing resistant crop varieties is advantageous not only because it decreases pest populations but also because it lessens reliance on insecticides. This reduction in insecticide use comes with several benefits, including decreased environmental impact and less disruption to biological control mechanisms. The availability of increasingly advanced tools for investigating both the genetic and phenotypic foundations of plant resistance is facilitating a deeper understanding of this phenomenon. This understanding can then be applied to the development of resistant cultivars (Stout & Davis, 2009). However, the development of such cultivars must be accompanied by a more quantitative approach to integrating plant resistance into integrated pest management (IPM) programs and quantifying its impacts. By combining a thorough comprehension of plant resistance mechanisms, the utilization of modern genetic tools for developing agronomically viable varieties, and a more quantitative approach to implementing host-plant resistance, the full economic and environmental benefits of plant resistance can be realized.

Conclusion

In the face of shifting climatic conditions, pests are intensifying their destructive capabilities and developing resistance to pesticides. Additionally, certain pesticides are exacerbating global warming. Environmental changes are also altering the interaction between hosts and plants, affecting plant defense mechanisms. Elevated temperatures and increased CO_2 levels are further weakening plant resistance to pests. Given these circumstances, there is a pressing need to develop climate-resilient varieties with stable resistance genes that can withstand changing climates. Increasing the use of host plant resistance in climate-smart pest management will enhance sustainability in crop production and environmental health.

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