Climate-smart pest management strategies: under changing climatic scenarios

Abstract:

In the face of changing climatic conditions, it's crucial to acknowledge their far-reaching impacts on humans, animals, and agricultural systems worldwide, where negative consequences often overshadow any positive outcomes. With global warming and climate change, previously minor insect pests are now poised to wreak havoc, leading to widespread pest outbreaks. As a result, the effectiveness of various pest control measures, including host-plant resistance, natural enemies, transgenics, bio-pesticides, and synthetic chemicals, may undergo significant shifts. Growers and researchers are actively devising Integrated Pest Management (IPM) strategies to minimize environmental harm while maximizing crop yields and economic benefits. Numerous studies highlight the necessity of reevaluating pest management practices and IPM strategies to adapt to novel environmental conditions and enhance the resilience of diverse agroecosystems to weather variability. This involves initiatives such as breeding climate-resilient crops, adjusting crop calendars, employing GIS-based risk mapping for crop pests, and exploring novel pesticides with alternative modes of action, informed by predictive modeling data. Thus, this chapter explores the potential of these techniques for climate-smart insect pest management.

Keywords: Climate change, GHGs, Climate-smart,Pest Management, Strategies.

1.INTRODUCTION

“Climate change refers to the long-term changes in the climate that occur over decades, centuries, or longer. It is caused by rapidly increasing greenhouse gases (GHGs) (carbon dioxide, nitrous oxide, nitrogen oxides, methane, and ozone) in the earth’s atmosphere due to primarily burning fossil fuels. Various definitions exist for climate change. As per the Intergovernmental Panel on Climate Change (IPCC), climate change refers to changes in the climate over time, either due to natural variability or as a result of anthropogenic activity. This usage is different compared to the framework convention on climate change, where climate change refers to the change of climate thatis attributed directly and/or indirectly to human activity, which alters the composition of the global atmosphere, and also to natural climate change observed over comparable periods” (IPCC, 2013). Another definition of the term climate change, according to the UN Climate Conference, 2022 “Climate change refers to long-term shifts in temperatures and weather patterns. These shifts may be natural, human-made, and primarily due to burning fossil fuels like coal, oil, and gases.” “This kind of periodic modification of the Earth’s climate is a result of changes in the atmosphere as well as the interactions between the atmosphere and various other geologic, chemical, biological, and geographic factors within the Earth system” (Anon., 2022). “Both natural, i.e., the environmental changes caused or influenced naturally, viz., sunspots and the sun cycle, ocean currents, forest fires, volcanic eruptions, and methane emissions, and anthropogenic, i.e., the environmental changes caused or influenced by humans either directly or indirectly, viz., chemical fertilizers, deforestation, vehicle emissions, industries, influence the earth's climate" (Mahato, 2014).

The change in climate leads to various deleterious effects, viz., changes in rain and snow patterns, stronger storms, higher temperatures and more heat waves, more drought and wildfires, thawing permafrost, less snow and ice, damaged corals, rising sea level, warmer oceans, changes in animals' migration and life cycles, and changes in plant life cycles. Further has various effects on humans (displaced people, poverty, loss of livelihood, malnutrition, risk of diseases, global food and water shortage), animals (habitat loss ., e.g.,polarbears, which rely on sea ice to access the seals as well as to rest and breed, due to increasing temperature, the sea ice is melting and causes habitat loss,migration, and species loss), and insects (population size, survival rate,and geographical distribution of pests).

" The number of people who are acutely food insecure worldwide has more than doubled, from 149 million people before the COVID-19 pandemic to 333 million people in 2023 (in 78 monitored countries by the World Food Program). Global hunger levels remained unchanged from 2021 to 2022. Protracted conflicts, economic downturns, and high food prices, further exacerbated by the high costs of agricultural inputs driven by ongoing and widespread conflict around the world, are at the root of high global food insecurity levels. This is aggravated by the effects of climate and weather extremes. The WMO report confirmed that 2023 was the warmest year on record, with the global average near-surface temperature at 1.45°C (with a margin of uncertainty of ± 0.12 °C) above the pre-industrial baseline. It was the warmest ten-year period on record.The global ocean experienced an average daily marine heatwave coverage of 32%, well above the previous record of 23% in 2016. At the end of 2023, most of the global ocean between 20° S and 20° N had been in heatwave conditions since early November; the rate of global mean sea level rise in the past ten years (2014–2023) is more than twice the rate of sea level rise in the first decade of the satellite record (1993–2002); CO_2 levels are 50% higher than the pre-industrial era, trapping heat in the atmosphere. The long lifetime of CO_2 means that temperatures will continue to rise for many years to come" (WMO, 2023). "Climate models indicate that between 1990 and 2100, there will be an average global warming of 1.4°C to 5.8°C due to the accumulation of these greenhouse gases. This increase is likely to cause faster surface temperature increases and more dramatic local variations. Forecasts of global warming obscure intricate local circumstances, the results of which will probably be an increase in the frequency of heat waves, droughts, and severe precipitation events" (Godfray*et al*., 1994).

2.Climate change threatening the Indian Agricultural sector

Agriculture is critical to ensuring India's food security and livelihoods(Chandana and Nadagouda, 2023). The agriculture sector employs almost two-thirds of the country's workers and accounts for 17% of GDP. During the past decades, climatic extremes and risks have intensified, threatening global agricultural production and food security (Pathak, 2023). India's climate varies greatly, with harsh winters in the north and tropical weather in the south (Aggarwal, 2003). Extreme weather conditions, such as heat waves, drought, flash floods, cyclones, and hailstorms, have a significant adverse effect on agricultural output (Aggarwal, 2022). The IPCC's Sixth Assessment Report emphasized that climate change can have a significant impact on agriculture (IPCC, 2021). India's agriculture has been more dependent on monsoonssinceancienttimes. Any change in the monsoon trend drastically affects agriculture (Mahato, 2014). Raising the temperature of the atmosphere can directly affect crop length, photosynthesis, and eventually agricultural production. In addition to increasing soil nutrient mineralization, decreasing nutrient usage efficiency, and increasing water loss, it can have an impact on insect population survival and dispersal. All of these factors translate into an increased need for irrigation water and plant nutrients. Due to its effects on soil fertility, erosion, droughts, floods, and irrigation water availability, climate change has a substantial indirect impact on agriculture. For Indian agriculture, a challenge is to provide food security while lowering emissions of GHGs. The task is more difficult because 85% of Indian farmers are marginal farmers who cultivate less than 1 hectare and small farmers who cultivate between 1 and 2 ha (Gupta and Pathak, 2016). Poor, small-holder farmers bear the brunt of climate change concerns because they rely more on climate-sensitive natural resources yet contribute the least to climate change. Agriculture is the primary sector responsible for food production worldwide. Agriculture and other land use changes (AFOLU) contribute up to 24% of GHG emissions from approximately 22.2 million km^2 of agricultural land (Pathak, 2023).

3.Impact of climate change on insect pests

Climate change has a substantial impact on agricultural insect pests. Climate change affects crops and the pests that prey on them, both directly and indirectly.The unpredictable occurrence of these extreme environmental conditions will probably be a greater challenge for most organisms, including insects, than will the gradual increase in average temperature (Godfray *et al*., 1994). Ectotherms have developed a variety of morphological, physiological, and behavioral adaptations that have evolved within a specific range of climatological conditions; new occurrences of extreme conditions constitute a challenge for these organisms (Addo-Bediako *et al*., 2000). Distributions of species, life cycles, community makeup, and ecosystem function are all impacted by changes in the global climate. A study of more than 1700 species found that 50% of these wild species are already impacted by climate change, and even a moderate scenario of global warming indicates that between 15% and 37% of the species may go extinct by the year 2050 (Hance *et al*., 2007).

Plants are essential to our existence, as they provide us with 98% of the oxygen we breathe and 80% of the food we eat. However, they are in danger. The FAO estimates that plant pests and diseases cause up to 40% of food crop losses annually (CYMMIT, 2024). The effects of disease outbreaks can be disastrous. The Irish potato famine of the 1840s, brought on by the fungus late blight, claimed the lives of about a million people and drove millions more to leave the country. Crop vulnerability to pests is further demonstrated by the recent, worst-in-decade invasion of the desert locusts over Africa. One small swarm of desert locusts can cover 1 km^2 and consume as much food as 35,000 people would in a single day, making it one of the most damaging pests in the world. The FAO warns that the outbreak might spark a humanitarian disaster (CYMMIT, 2024).

3.1.Herbivory in relevance to elevated temperature

“Understanding how climate change impacts species, populations, communities, and ecosystems, as well as the underlying mechanisms, might improve predictions of its total impact. Climate change models generally overlook the impact of herbivores, which play a crucial role in ecosystem structure and function.A model demonstrating how the development rates of insects and host plants at different temperatures can impact the spread of host-specific insect herbivore species. In the northern region (low-temperature index), the host plant grows too slowly to support insect development, while in the south (high-temperature index), the plant grows too quickly. The insect herbivore can only synchronize its phenology with the host plant anywhere in the middle of its range. The growth period is assumed to be during the summer, and the single diapause is during the winter. The low-temperature requirement for diapause indicates where temperatures lower than those favorable for morphogenesis are needed for successful life-cycle completion. By combining fast or slow growth rates with temperature-related diapause, predictions as to the life cycle of a species and its response to climate change through changes in its distribution (range) are possible. Fast-growing, non-diapausing species are likely to be multivoltine and will respond the greatest to temperature elevation through expanding their ranges. Fast-growing species that are not dependent on low temperatures to induce diapause are likely to be multivoltine or annual and will respond through range expansion. However, those fast-growing species that do need low temperatures for diapause (again, millivoltage or annual) are likely to respond to climate change with some range contraction. Slow-growing species that need low temperatures to induce diapause are likely to be unable to expand their ranges and may be detrimentally affected by climate change”(Bale *et al*., 2002). “This simple framework could be applied to a large range of insects, and by knowing two parameters (growth rate and diapause requirement), potential range and distribution changes could be estimated” (Bale *et al*., 2002).

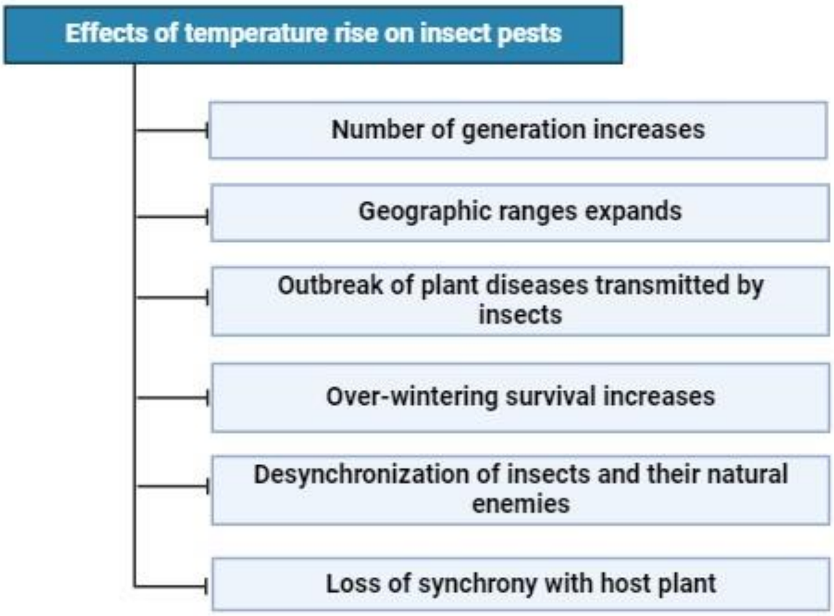

Fig. 1:Effect of temperature rise on insect pests

The physiology of insects is highly sensitive to temperature variations; a rise of 10°C typically causes their metabolic rate to almost double. In this regard, numerous studies have demonstrated that rising temperatures typically hasten the consumption, growth, and migration of insects. These effects can then have an impact on population dynamics through the manipulation of fecundity, survival, generation duration, population size, and geographic range (Bale *et al*., 2002) (Fig. 1.). Species that cannot adapt to high temperatures struggle to maintain their numbers, while others flourish and reproduce quickly. Temperature affects metabolism, metamorphosis, mobility, and host availability, all of which impact the likelihood of alterations in pest dynamics and population (Skendžić*et al*., 2021). The distribution and behaviour of modern insects lead to the hypothesis that higher herbivory would be associated with rising temperatures. It can be assumed that a temperature rise should be correlated with an increase in herbivory given the distribution and behavior of insect pests (DeLucia *et al*., 2008), as well as the changes in the growth rate of the insect population. Because the current temperature is already very close to the ideal range for pest development and growth, it is therefore anticipated that insect populations in tropical zones will grow less quickly as a result of climate change, while insect populations in temperate zones will grow faster (Deutsch *et al*., 2018).

As temperatures rise, insect pests are projected to change their range from the tropics and subtropics to temperate zones at higher altitudes, causing alterations in cultivation areas for their host plants. This could result in a rise in the abundance of tropical insect species as well asa sudden outbreak of pests, which could wipe out some crops entirely. Meanwhile, a drop in the relative abundance of the population of temperature-sensitive insects may result from warming in temperate regions. Polar regions are typically immune to insect outbreaks due to low temperatures and frequent frosts. Future forecasts of climate change and a rise in the frequency of droughts are anticipated to lead to an increase in the frequency of insect outbreaks in temperate zones. Therefore, these continuous changes in insect-pest range and distribution brought on by climate change may have an impact on the structure, diversity, and ecosystem functioning of specific regions (Fand *et al*., 2012).

3.2.Herbivory in relevance to elevated CO_2

Several studies have examined the impact of CO_2 enrichment on herbivores, including changes in host plant traits and herbivore responses to these conditions. Plant physiology is influenced by elevated CO_2, which has an immediate impact on plant productivity and biochemical composition. The chemical makeup of plants impacts trophic interactions, breakdown, and atmospheric CO_2 concentrations (Lindroth, 2010). While the effects of enriched CO_2 on plants are not always the same, they frequently show improved photosynthetic activity, higher productivity, and a larger leaf area or biomass while growing in elevated CO_2 environments. Increased CO_2 may also change the primary and secondary metabolisms of plants. A "nitrogen dilution effect" results from changes in the C/N ratio and increased carbon availability in plant tissues, which affect the amount of nitrogen in those tissues. Because of this low nitrogen content, high C/N ratio, and possible effects on plant secondary metabolism, there is less leaf protein present, which lowers the nutritional value for herbivores (Lincoln *et al*., 1986). Elevated CO_2 levels are likely to impact plant secondary chemistry by increasing carbon supply and allocation for secondary and structural compound synthesis.

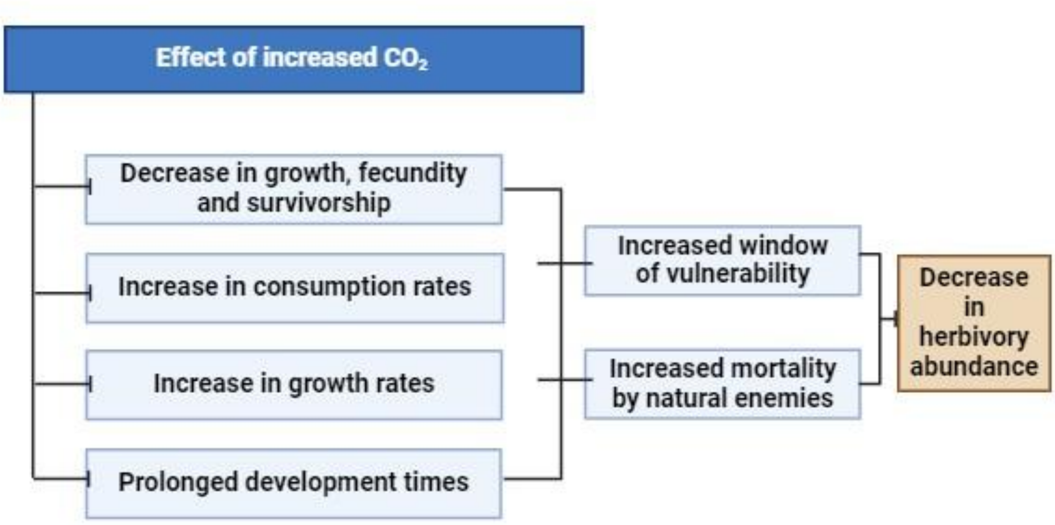

Fig. 2:Effect of increased CO_2 on insect pests

Over the last 50 years, rising CO_2 levels have caused a significant shift in atmospheric composition. Photosynthesis depends on CO_2, and high concentrations of this gas might affect plant physiology. Elevated CO_2 increases rates of photosynthesis and stomatal openings and reduces transpirational water loss. As CO_2levels rise, the amount of CHO in leaves also increases;however, nitrogen levels decrease (Subedi *et al*. 2023).Herbivores were previously thought to react to altered plant primary and secondary metabolism under elevated CO_2 by decreasing their growth rates and lengthening their development times, decreasing food conversion efficiency, and increasing food consumption to make up for the plant's decreased nutritional quality. Compared to ambient CO_2 environments, these losses in herbivore performance under CO_2 enrichment could lead to an increase in natural enemy-imposed mortality, which would ultimately reduce herbivore abundance, richness, and variety (Fig. 2). (Cornelissen, 2011).

3.3.Herbivory in relevance to variation in precipitation

Changes in the quantity and frequency of precipitation are the major indicators of climate change. As seen in many events, the frequency of rainfall has decreased while the intensity of rainfall has increased. This type of precipitation pattern has favoredthe occurrence of floods and droughts. Insects that overwinter in soil are directly affected by overlapping precipitation, i.e., heavy rainfall leads to floods and stagnation of water, which threatens survival and their diapauses. Furthermore, flooding and severe rains have the potential to sweep away insect eggs and larvae (Shrestha, 2019) (Fig. 3.). Heavy rains can wash away small-bodied pests, including aphids, mites, jassids, and whiteflies, among others. Variable precipitation could have a key impact on the insect population.

For instance, in grassland plots, Staley *et al*. (2007) investigated the effects of drought and increasing summer rainfall on the soil-dwelling wireworm (*Agrioteslineatus* L.). Particularly when cultivated in grassland plots, wireworms are a highly destructive pest of crops including potatoes, corn, sugar beetroot, etc., and predictions indicate that their impact will likely increase due to climate change. Compared to ambient and drought conditions, Staley *et al*. (2007) observed that wireworm populations grew quickly in the topsoil due to higher summer rainfall occurrences (Gregory *et al*., 2009).

Drought affects herbivorous insects in a few ways: (I) dry regions may offer favorable climatic conditions for the development and expansion of herbivorous insects; (II) certain insect species are drawn to plants that are stressed by drought. For instance, when plants lose moisture through transpiration, water columns in the xylem fracture or cavitate, generating an ultrasonic acoustic emission that is picked up by dangerous bark beetles (Scolytidae); (III) plants under stress from drought produce fewer secondary metabolites, which serve as defense mechanisms, making them more vulnerable to insect attack (Yihdego*et al*., 2019).Furthermore, studies have demonstrated that plants under water stress may experience a reduction in their biological functions, which increases their susceptibility to pests and illnesses. Additionally, research has shown that because the host is smaller or less available, aphids reared on water-stressed plants have a reduced rate of parasitism. Last but not least, sporadic water stress on trees yields better results for insect herbivores like sap-feeders than continuous stress (Cornelissen, 2011).

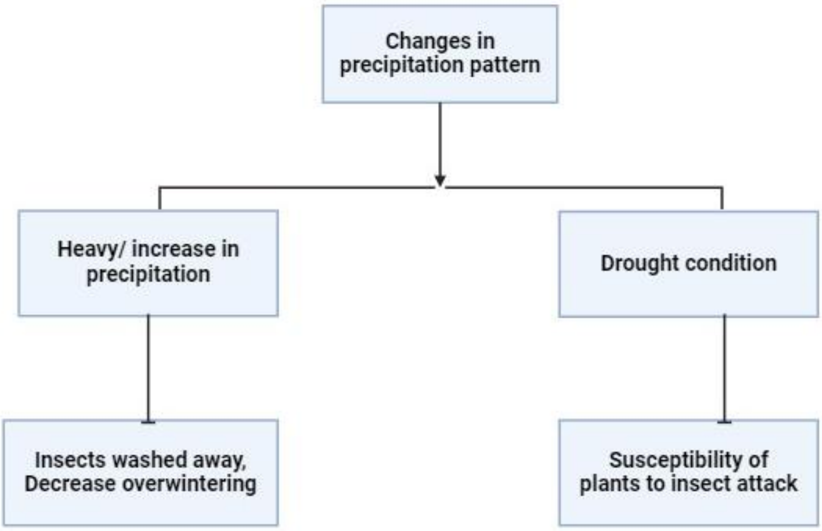

Fig. 3:Effect due to changes in precipitation pattern

4.Impact of climate change on insect pest management strategies

According to Painter (1968) and Dhaliwal and Divari (1993), host plant resistance is one of the most environmentally beneficial methods for controlling damaging insect pests on crops. The plant can reduce the damage caused by insect pests through a variety of mechanisms, including antixenosis, antibiosis, and tolerance. Climate, sunlight, soil moisture, air pollution, and other environmental conditions all have a significant impact on the expression of host plant resistance. The relationships that insect pests have with their host plants could change if these environmental conditions change (Sharma and Oritz, 2000). Stressful environments decrease a plant's defenses against insect pests, which increases crop damage and pest outbreaks. As global temperatures rise and water stress increases, tropical nations such as India may experience a significant reduction in sorghum yield as a result of the midge, *Stenodiplosissorghicola,* and the spotted stem borer, *Chilopartellus*, breaking down their resilience (Sharma *et al*., 2005). Because they do not have the necessary adaptations to cope with inadequate climatic circumstances, insect pests— which gain from weakened host defenses—will be more severely affected. Certain plants can directly react to insect damage by altering their chemical makeup, which makes their tissues less conducive to insect pest growth and survival. If climate changes encourage the introduction of non-resistant crops or cultivars into new locations, problems with new insect pests will arise. One way to benefit from climate change could be throughthe introduction of new crops and cultivars.

Insect-resistant transgenics expressing the Bacillus thuringiensis (Bt) insecticidal protein (delta-endotoxin) were created as a new development in integrated pest control (Kranti *et al*., 2005). Transgenic plants reduced toxin protein levels during high temperatures, elevated CO_2 levels, or drought, resulting in lower insect pest resistance (Chen *et al*., 2005). High temperatures in Texas, USA, caused the cotton bollworm (*Heliothisvirescens*) to devastate Bt cotton crops (Kaiser, 1996). The environment's impact on transgenic expression, locally resistant insect populations, insufficient management leading to the development of resistance, and insufficient production of the toxin protein are all potential reasons why insect control efforts fail. Therefore, it's critical to comprehend how climate change affects transgenic plants' ability to control pests (Sharma and Oritz, 2000).

Global warming will alter the relationships between insect pests and their natural enemies, which will lead to changes in the status of particular pest species, both positively and negatively. The timing of various insect groups' diurnal activity patterns will also fluctuate in response to temperature fluctuations, and variations in interspecific interactions may also affect how well natural enemies work as pest controllers. In the future, one of the main concerns for pest management program will be quantifying the impact of climate change on the activity and efficacy of natural enemies. Synthetic insecticide misuse is the cause of today's sensitivity to environmental pollution, health risks to humans, and pest recurrence. The environment greatly affects natural plant products, nematodes, bacteria, fungi, viruses, and synthetic insecticides. One of the main factors influencing pesticide efficacy and toxicity, whether advantageous or detrimental, is temperature. It has been discovered that the response relationship between temperature and efficacy varies based on the insecticide's mode of action, the type of target, the application technique, and the amount of insecticide ingested or contacted (Skendžić*et al*., 2021). At higher temperatures, the insect growth regulator (IGR) diflubenzuron produced rapid mortality; at 35°C, it was more effective.This was most likely caused by the fact that this IGR is only effective during insect moults and that insect growth and moulting rates rise with increasing temperatures (Amarasekare and Edelson, 2004). When exposed to solar radiation, especially in the ultraviolet (UV) region of the spectrum, entomopathogens that are used as biocontrol agents become unstable (Skendžić*et al*., 2021). According to Chen and McCarl (2001), pest treatment costs under the 2090 climate projections show increases of 3–10% for corn, soybeans, cotton, and potatoes and mixed results for wheat. They also project a $200 million annual loss to society as a result of the effects of pesticide treatment costs related to climate change in the United States. As a result, it is necessary to create effective pest management plans that will hold up in the face of future global warming. In light of climate change, farmers will require a range of pest management techniques that can generate sustainable harvests.

5.Climate-smart pest management (CSPM)strategies in the changing climate scenario

Adaptation methods that could lessen the harmful effects of current pests and lower the risks of introducing new illnesses and pests have been identified. Climate change and rapidly expanding global trade will lead to more uncertainty and a higher frequency of both new and old pests. Modified integrated pest management (IPM) techniques, climate and insect pest population monitoring, and the application of modeling prediction tools are the most often stated strategies (Fig. 4).(Skendžić*et al*., 2021).

***(CSPM- Climate-Smart Pest Management**

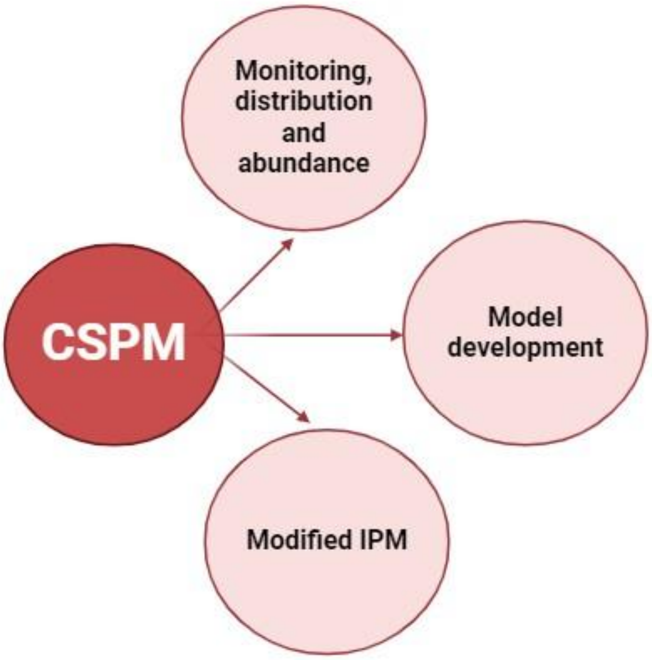

Fig. 4. CSPM strategies for climatic change.

5.1.Monitoring, abundance and distribution

Having access to long-term data is critically necessary to assess if the population dynamics of insect pest species are being affected by climate change. It is very difficult to fully assess changes in pest populations under changing climate regimes and to anticipate future population dynamics without these crucial baseline data. Long-term monitoring of pest populations and behavior, particularly in climate change-vulnerable areas, may provide some of the first indications of biological reactions to climate change. Some of the earliest indicators of the biological response to climate change may come from long-term monitoring of pest populations and behavior, especially in areas where climate change is a concern. Since many insect pests are transboundary, effective monitoring and risk assessment require a worldwide management approach (Skendžić*et al*., 2021). As a result, biosecurity and pest management will both need adaptive responses.

5.2.Model development

“The potential distribution of insect pest species is primarily estimated by ecological niche models (ENMs). They are further divided into two groups, viz., correlationalmodels and mechanistic models. The correlational model uses correlated values of environmental variables and records of occurrence to make predictions about future changes in the geographic distribution of species, assess extinction rates, and set priorities for biodiversity conservation.It has become a cornerstone of climate change policy. These models identify statistical relationships between the current geographic distributions of a given species and climate variables, which are then implemented into projections of climate change to suggest climatically suitable habitats for that species in the future. Mechanistic models are predictive tools that use the values of environmental variables ina given area in combination with knowledge about the environmental tolerances of a given species. Future species distributions are then predicted through a process of elimination, whereby regions that constrain physiological performance to the extent that they affect the ability to survive, grow, or reproduce are excluded from the final distribution" (Skendžić*et al*., 2021).

5.3.Modified Integrated Pest Management

Modified cropping practices and adaptive management strategies are needed to reducethe impact of agricultural pests on crops in a changing climate. These may include: (I)planting different crop varieties; (II) planting at different times of the year to minimizeexposure to pest outbreaks; and (III) increasing biodiversity at field margins to increase thenumber of natural enemies. Pheromones and allelochemicals are two crucial ways that insects sense their surroundings. They contribute significantly to several IPM strategies, including monitoring, trapping, push-pull tactics, biological control, and mating disruption. The use of pheromones and allelochemicals in their current form is predicted to become less successful as the climate heats and microclimates become more changeable. This may need the inclusion of a synergist or other adjuvant to lessen their volatility under high-temperature circumstances. Furthermore, several biopesticides that are based on bacteria, nematodes, fungi, or entomopathogenic viruses are very sensitive to changes in their environment. Certain management strategies may become less successful with rising temperatures and falling relative humidity; synthetic insecticides should exhibit a similar effect. In this situation, the development of novel approaches to managing pests and potential innovations in insecticide and attractant/repellent compositions should be the main priorities (Skendžić*et al*., 2021). The adaptive capacity of agricultural production systems will depend on several biological, economic, and sociological factors. The ability of local communities to adapt their pest management practices will depend on their physical, social, and financial resources (Sutherst*et al*., 2011).

Gaining further insight into how global warming affects the effectiveness of several synthetic pesticides, their durability in the environment, and the emergence of pest population resistance to certain insecticides is imperative (Fand *et al*., 2012). Thus, it would seem appropriate to think about the application of effective biological control agents or the introduction of crop types resistant to insect pests that are produced by genetic engineering or normal genetic breeding.

6.Climate change and Integrated pest management approaches

6.1.Cultural control

It will be necessary to modify farming practices and employ adaptive management techniques to lessen the damage that agricultural pests do to crops. This can entail: (1) growing a variety of plants; (2) planting at different times of the year to reduce exposure to pest outbreaks; and (3) enhancing the variety of habitats on edges to encourage the presence of natural enemies (Andrew and Hill, 2007).

6.2.Crop production and diversification

By lowering insect outbreaks and pathogen transmission and protecting crop production from increasingly frequent extreme weather events and increased levels of climate variability, crop rotation and diversification can increase the resilience of agricultural production (Lin, 2011). Crop rotation can help control illnesses, whose incidence is expected to rise due to climate change. Planting pulse, oilseed, and forage crops in a cereal cropping system, for instance, breaks disease cycles (Krupinsky *et al*., 2002).

6.3.Biological factors

In terms of methodology, most evaluations of predators and parasitoids have been carried out at steady-state temperatures. According to research by Bahar *et al*. (2012), temperature fluctuations in lab settings, especially at lower temperatures, can significantly alter the time that pest herbivores—in this example, the diamondback moth—and their parasitoids spend developing. Short-term temperature variations can put pest species and their natural enemies under a lot of stress, which can subsequently have a big impact on how they interact (Chidawanyika*et al*., 2012). Temperature extremes and fluctuations have an impact on the biology of insects in agroecosystems, affecting both pests and natural enemies, which would lessen the effectiveness of biocontrol agents. It will be challenging to forecast these effects without a complete grasp of the tritrophic relationships between species (Thomson *et al*., 2010).

6.4.Reproductive control

The sterile insect technique (SIT) is an essential approach for controlling insects that release sterile males caused by radiation into wild populations to decrease the amount of progeny after mating with wild females. It is a crucial technique used globally to manage *Ceratitiscapitata* (Tephritidae: Diptera). One strain of *C. capitata* possesses a temperature sensitivity gene, tsl, which causes homozygous female embryos to die at high temperatures after 24 hours of development, unlike males (Robinson, 2002). The impact of the tsl gene mutation or the effect of radiation on released males in the wild is still unknown, although females remain temperature-sensitive throughout their lives. Populations in South Africa grow when enough days are acquired, and they decline when temperatures drop below the minimum essential temperature. The tsl mutation-expressing animals show a higher critical thermal maximum and longer field survival than wild-type individuals, suggesting that the sterile insect method might work better in a warming climate (Nyamukondiwa *et al*., 2013). This benefit of sterile males raised in laboratories may increase their use as a pest control tool in a warmer environment.

6.5.Semiochemical

Semiochemicals, or signaling chemicals, are essential to integrated pest management (IPM) because they alter the behavior of other living things. Pheromones and allelochemicals are two important senses that insects use to detect their surroundings. They are perfect for a variety of IPM techniques because they may be used for monitoring, trapping, mating disruption, push-pull strategies, and biological controls. The efficiency of semiochemicals can be significantly impacted by temperature, humidity, and air velocity (Heuskin*et al*., 2011).Temperature has also been shown to be critical environmental variable influencing volatile release rates in waterbuck odors to control tsetse fly (Shem *et al*., 2009) and sawfly sex pheromones (Johansson *et al*., 2001). As the annual climate warms across agricultural landscapes and as microclimates become more variable, it is anticipated that the use of these volatiles in their current forms may become less effective and may require a synergist or other compounds to reduce their volatility under high-temperature regimes.

6.6.Pesticide

Over the 1960s, there has been a 15–20-fold rise in pesticide use due to the doubling of maize, wheat, and rice output globally (Oerke, 2006). Furthermore, there has been a rise in crop loss from pests along with the increase in crop production brought about by the adoption of high-yielding cultivars, management of soil and water, fertilization, and cultivation techniques. A lot of the innate resilience in crops has been bred out, making many new varieties more dependent on pesticides since they are less tolerant to competitors and herbivory (Oerke, 2006). Using a variety of pesticides to ensure food security is expected to be one of the more sought-after management strategies due to the anticipated increased insect pest outbreaks and the requirement for global food production to expand by 50% tofulfill the needs of the world's population by 2050 (Chakraborty and Newton, 2011).

6.7. Long-term monitoring

One of the key requirements to determine if climate change is changing the population dynamics of pest species is having access to long- term data. Without this key baseline data, it is extremely difficult to fully assess changes in pest and beneficial populations with changing climate regimes and predict future population dynamics. However, data covering population dynamics of populations over 50 years are very sparse, with only a few examples, such as annual light trap catches in Japanese rice paddy fields for 50 years (Yamamura *et al*., 2006), aphid suction trap catches at Rothamsted, UK, also for 50 years (Bell *et al*., 2015), and a 1910-year record of locust outbreaks in China based on a reconstructed time and abundance series (Tian *et al*., 2011). Predicting pest outbreaks is challenging in most agroecological zones because of a lack of long-term data. Modeling population dynamics to match changing climate regimes is often uncertain. Predictions of community assemblage change in agroecosystems with climate change are further complicated by the lack of any long-term assessment of parasitoids/predator–host/prey interactions and changes in trophic-level interactions.

7.Climate change and future challenges ahead

The increase in global temperatures and changes in rainfall patterns could lead to a reduction in crop growing seasons and severe issues with early insect infestations. Therefore, with a changing environment, several useful cultural methods like crop rotation and planting dates will be less or useless in controlling crop pests. As a result, crop calendars must be adjusted to reflect the shifting crop environment. In light of the changing environment, crop growers must adapt their insect management techniques to match anticipated changes in pest incidence and crop loss severity.The increase in global temperatures and changes in rainfall patterns could lead to a reduction in crop growing seasons and severe issues with early insect infestations. Therefore, with a changing environment, several useful cultural methods like crop rotation and planting dates will be less or useless in controlling crop pests. As a result, crop calendars must be adjusted to reflect the shifting crop environment. In light of the changing environment, crop growers must adapt their insect management techniques to match anticipated changes in pest incidence and crop loss severity.Geographic Information System (GIS) technology is a valuable tool for entomologists since it facilitates the connection between insect pest outbreaks and the biographic and physiographic elements of the terrain. As such, it is best applied in pest management programs that cover a large area. By forecasting and charting patterns of prospective shifts in the geographic distribution of insect pests, as well as identifying agro-ecological hotspots and future pest risk areas, GIS can be used to investigate how climate change will impact the development, incidence, and population dynamics of these pests (Sharma *et al*., 2005).Some researchers have reported that, in addition to their insecticidal impact, the use of neonicotinoid pesticides to suppress sucking pests causes salicylic acid-associated plant defense responses that improve plant vigor and abiotic stress tolerance. This provides insight into the investigation of pesticides' potential to improve plants’ ability to withstand stress. It is necessary to identify these additional chemicals for application in crop pest management in the future.

8. Conclusion

Addressing the challenges posed by climate change and pests requires more than technological solutions alone. It also necessitates policy support, capacity building, and stakeholder engagement at local, national, and international levels. Governments, research institutions, non-governmental organizations, and communities must collaborate to develop and implement policies that promote sustainable agriculture, support farmer education and extension services, and facilitate the adoption of climate-smart pest management practices.

DEFINITION:

Climate-smart pest management (CSPM): It is a cross-sectoral strategy that aims to decrease pest-induces crop losses, increase ecosystem services, decrease greenhouse gas (GHG) emissions per unit of food produced, and strengthen the resilience of agriculture systems in the face of changing climates (Heeb*et al*. 2019).

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