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THE IMPACT OF VARIOUS CLIMATE CHANGE FACTORS ON AGRICULTURAL INSECT PESTS, CROP PRODUCTION, AND THEIR MANAGEMENT STRATEGY IN INDIA - A REVIEW

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ABSTRACT: In conclusion, agricultural insect pests pose a major threat to food security, especially in the face of climate change. To address this problem, effective management strategies must be implemented. Climate change has become a globally recognized reality. It has a serious impact on the diversity, distribution, existence, reproduction, development, growth and phenology of insect pests and plant species. Protecting food in the 21st century will be the greatest challenge for humanity in the coming years, given the decline in production efficiency due to the depletion of the natural resource base, the drastic effects of climate change on the diversity and abundance of insect pests, and the scale of crop losses. Understanding the biology and behavior of pests in relation to the environment is crucial because climate change will change their distribution and behavior. Integrated pest management strategies, which combine cultural, biological and chemical approaches, should be used to reduce reliance on pesticides and minimize environmental impact. Forecasting systems based on historical records, remote sensing data, and citizen science reports can provide early warnings and help mitigate pest outbreaks. Developing pest-resistant and drought-resistant crop varieties can enhance food security and reduce reliance on chemical controls. Dealing with climate change is very daunting. The impacts of climate change on crop production, mediated by changes in the numbers of severe insect pests, should be carefully considered when planning and implementing adaptation and mitigation strategies for future pest management programmes. It is therefore necessary to consider the potential impacts of climate change on crop health in a coordinated manner and to develop effective measures to mitigate the impacts of climate change on food security. Insurance programs and financial tools help farmers manage risks and invest in pest management strategies.

Key words: Climate change, crop production, temperature, precipitation, CO_2, drought, insect pests, food security.

INTRODUCTION

Climate change is a worldwide threat that is unavoidable and immediate which encompasses a combination of natural and anthropogenic changes in the environment. Worldwide attention has been attracted by recent changes in global climate phenomena and consequent losses. Climate change, according to the Intergovernmental Panel on Climate Change (IPCC), is described as “any change in climate over time, whether due to natural variability or as a result of human activity”. Human activities are responsible for much of the warming that has been observed over the last 50 years. From 1990 to 2100, the global mean surface temperature is expected to rise by 1.4 to 5.8°C. In the next 100 years, if temperatures increase by around 2°C, the detrimental global warming effects will begin to spread in much of the world’s region and (**IPCC, 2001**). In addition, CO_2 levels rose from 280 ppm to 401 ppm in 2015 (Mauna Loa Observatory: Hawaii).

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Insects constitute over half of the estimated 1.5 million organism species of the biodiversity identified so far on the planet and are fundamental to the structure and function of ecosystems. Insects are among the most susceptible groups of organisms to climate change as they are ectothermic, so thermal changes have strong direct effect upon their growth, reproduction and existence (**Bale *et al*., 2002**). The effects of climate change on insect pests are of greater significance because insects are involved in many biotic interactions, such as plants, natural enemies, pollinators and other organisms, which play a major role in the ecological functioning of insect pests. The impact of climate change on arthropod extinction rates is 100 to 1000 times greater than what has occurred previously, with about 45 to 275 species becoming extinct on a daily basis. An increase in a temperature rise of 6°C would result in the mass extinction of species, including humans. For example, due to hot temperatures (like heat waves) related to climate change, have resulted in a decrease in bumblebee populations by 46 per cent in North America and by 17 per cent across Europe compared to the base period of 1901 to 1974. In India Basavarajappa S, has observed a 2 per cent decline in rock bee, *Apis dorsata* colonies every year in Mysore due to increase in temperature, altering its local climate.

The world has experienced substantial advancements in science and technology over the past several decades, leading to rapid economic growth and increased agricultural production (**Pingali and Abraham, 2022**). Technological innovations and the industrial revolution have greatly impacted agricultural practices, producing heightened output. However, the 20th century and the early years of the 21st century have seen a significant increase in the global population, threatening both environmental stability and food security (**Wudil *et al*., 2022**). With the anticipated meteoric rise in food demand due to the rapidly growing population by 2050, agricultural production must increase to meet such demand. Research suggests that increasing crop production and better managing produced crops, rather than expanding land, is the best way to ensure adequate food supply for the growing population (**Fróna *et al*., 2019**). Managing produced food is important to ensure food adequacy and accessibility but is beyond the scope of this review. Factors such as global warming, frequent droughts, changing atmospheric carbon dioxide (CO_2) concentrations, weather disruptions, and other climate-related variables, however, continue to challenge crop yields (**Lin *et al*., 2022**). These abiotic factors also influence pest biology, performance, population dynamics, and their interactions with plants and natural enemies, all of which are critical factors in determining crop yield (**Cannon, 1998**). Increased pest populations and frequent outbreaks due to weather disruptions and climate-related changes can negatively impact crop productivity and availability, ultimately threatening food security (Fig. 1). This review aims to analyze ongoing and anticipated climate change impacts, particularly elevated CO_2 concentrations, droughts, and temperature, on insect pest biology and ecology. Additionally, the paper presents modern pest monitoring technologies and prediction tools to create modified integrated pest management (IPM) strategies that can effectively combat or manage pest adaptation and pressure on crops while considering the effects of climate change, ultimately ensuring adequate food production.

Climate Change, Crop Production, and Agricultural Insect Pests

The continuous alteration of the climate has been well documented by scientists, with evidence supporting the claim (**Subedi *et al*., 2023**). The Intergovernmental Panel on Climate Change (IPCC) defines climate change as "a change in the state of the climate that can be identified (by using statistical tests) by changes in the mean and/or the variability of its properties that persists for an extended period, typically for decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity". Climate-related variables, such as temperature, water availability, and CO_2 concentration, play a significant role in determining the characteristics of food-generating ecosystems, including freshwater and marine systems, agriculture, and forestry. Any changes to these variables threaten global food production (**Field *et al*., 2014**).

Human activities, particularly the use of fossil fuels and industrialization, have been

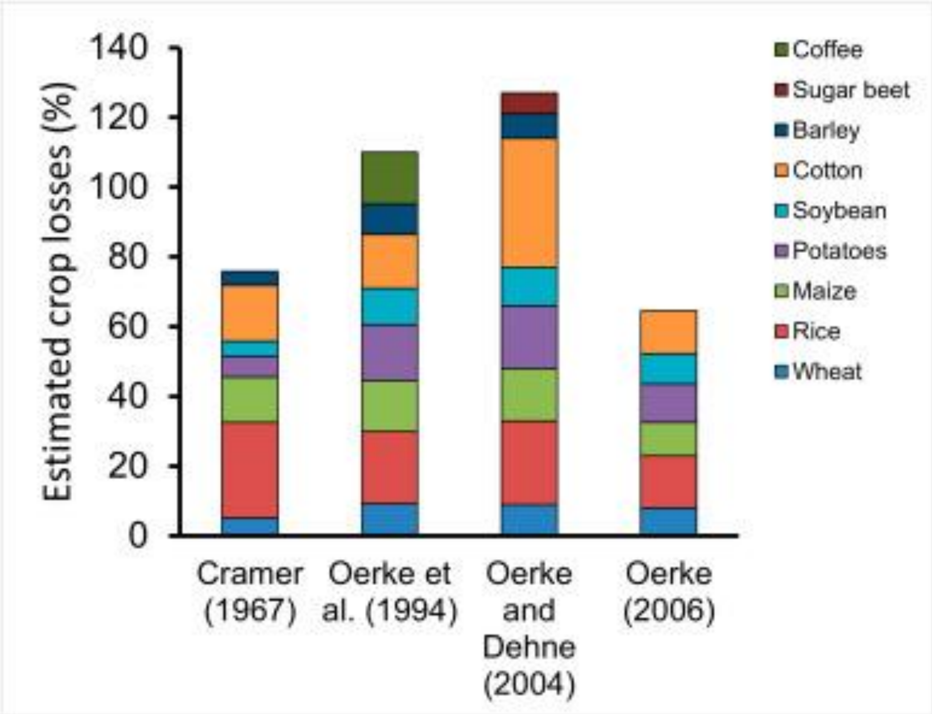

Fig. 1. Global estimates of crop losses due to insect pests/animal pests (Sharma *et al.*, 2017).

largely responsible for the observed global warming over the past century. Climate models predict that the Earth will experience a rise in temperature of 1.4–5.8°C over the next century. The increase in atmospheric greenhouse gas (GHG) concentrations, particularly CO_2, is the main contributor to this global warming. The thermal infrared radiation that is reflected from Earth's surface gets absorbed by GHGs, including CO_2, methane (CH_4), nitrous oxide (N_2O), and chlorocarbons (CFCs), and subsequently is released back to the surface, trapping more heat energy and causing global warming (**Rogelj *et al*., 2018**). Human activities have also been linked to extreme weather and climate events, such as heat waves, temperature extremes, increased drought, and flooding, after the 1950s. Moreover, as climate change intensifies, the rate and strength of heat waves and intense precipitation events are expected to increase.

Climate Change Effects on Crop Production

Agricultural activity primarily relies on climate variables, including temperature, water availability, and weather conditions for crop production. Because of the heavy dependency of agriculture on climate variables, any changes or disruptions in these variables could enormously influence crop yield and productivity (Fig. 1) **(Myers *et al*., 2022)**. Research on the effect of these variables on crop production has shown neutral and positive to negative impacts (Fig. 2) at both individual and community levels, with reports of more negatives than positives.

Elevated Temperature

The rise in global temperature resulting from climate change has threatened plant growth, production, and distribution (**Priya *et al*., 2019**). According to predictions, global crop production is expected to decrease by approximately 10% by the mid-21st century, jeopardizing global food security. Additionally, if the average daily calorie intake in 2050 rises to 3600 kcal per day, equivalent to the current diet in the United States, a 70% increase in food production will be necessary. Temperature directly impacts crop plant physiology and imposes temperature-related limitations on various factors such as growth, development, yield, and geographical distribution (Fig. 2). In northern regions with shorter growing seasons, the increased temperature has been observed to enhance crop production due to the rise in air temperature. Nevertheless,

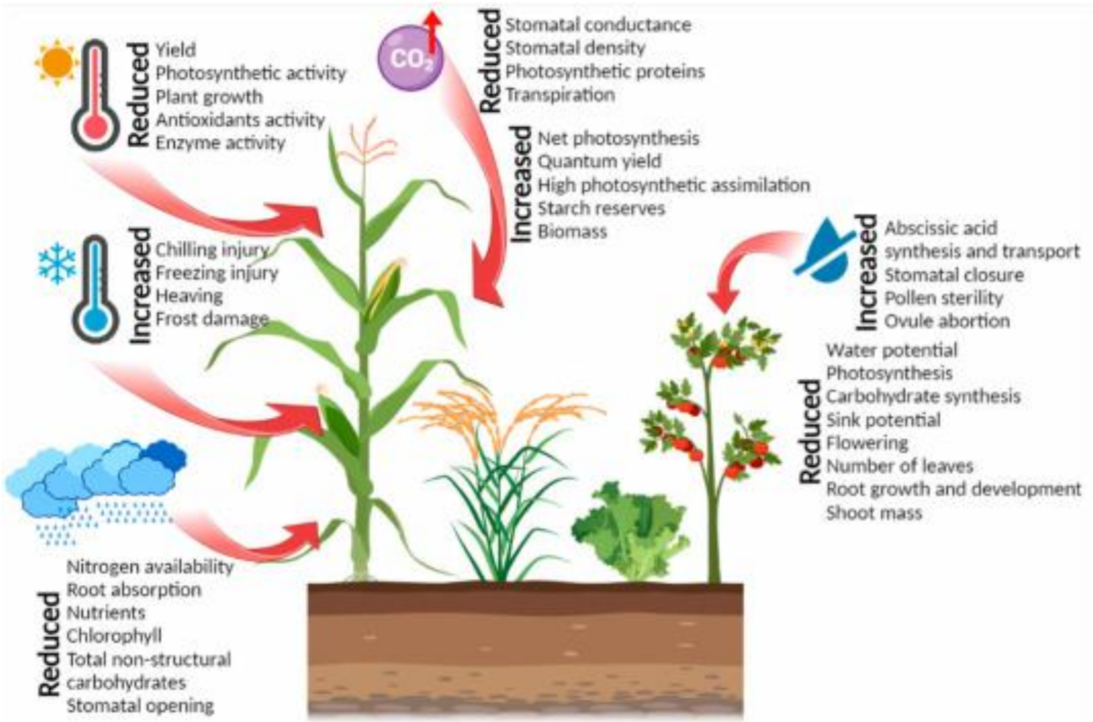

Fig. 2. Impact of climate change on crops (Myers *et al*., 2017 and Myers *et al*., 2022).

as global temperatures continue to rise, the negative effects of climate change are expected to worsen in the future, despite current positive outcomes (Table 1) **Arnell *et al*., 2019**). By the end of the 21st century, the mean growing period temperature is predicted to surpass the highest temperatures recorded in the past century. Additionally, the rapid rise in daily minimum temperature (Tmin) compared to the daily maximum temperature (Tmax) could potentially impact temperature-sensitive plant physiological parameters and, ultimately, crop production. For instance, a 50% decline in wheat yield in Australia was predicted due to increased leaf senescence under similar precipitation conditions with a two-degree mean growing season temperature variation. Floods, drought, and hot spells frequency are projected to increase with changing climate, leading to shorter crop-growing seasons (**Lesk *et al*., 2022**). Climate model simulations indicate that an increase in temperature increases the risk of lower precipitation during growing seasons for maize, winter wheat, and rice, but mixed results for soybean and spring wheat have been reported. Major heat waves are also projected to become more frequent, further impacting crop productivity (**Wang *et al*., 2023**). The increased atmospheric air temperature results in a vapor pressure deficit, leading to increased water demand in the atmosphere, which is then replenished through soil moisture evaporation. The loss of soil moisture can cause water scarcity, frequent drought spells, and decreased crop yield (Fig. 2).

The global average temperature is expected to increase by at least 4°C by the end of the 21st century, due to the increased frequency and intensity of drought and heat waves. Temperature has a strong effect on insect growth, survival and reproduction and enrols a major role in controlling the development and growth of their host plants. In addition, the development of plant secondary chemicals as well as the structural characteristics used to protect against herbivores are influenced by temperature. Thus, for both insects and plants, temperature has potentially significant consequences (Fig. 3). Phytochemical and morphological changes in host plants are caused by changes in temperature. For example, at night temperatures of 17°C, the concentration of catecholic phenolics (chlorogenic acid and rutin) in tomatoes was significantly higher than at other temperatures (**Harthik *et al*., 2021**).

Table 1. Anticipated rise in crop damage caused by insect pests in regions due to a climate warming of 2°C. The projected alteration in future crop yield reduction is for the average geographical area within each country, while being correlated with the current average crop yield per unit of cultivated land for wheat, rice, and maize (adapted from Deutsch *et al*., 2018)

Regions	Crop production loss (%)		
	Wheat	Rice	Maize
Asia	17	32	23
Europe	18	NA	12
Mesoamerica	NA	NA	3
North Africa	2	NA	NA
North America	18	1	32
North Asia	13	NA	2
Oceania	4	NA	NA
South & South East Asia	10	59	7
South America	4	3	11
Sub-Saharan Africa	NA	NA	8
West & Central Asia	14	2	2

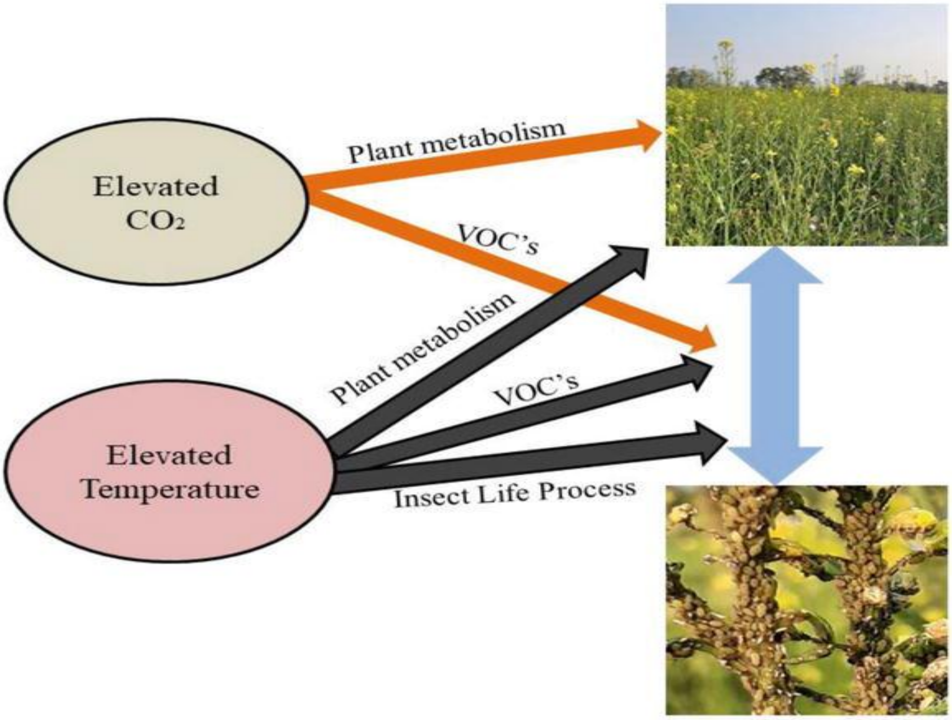

Fig. 3. Effects of elevated CO_2 and temperature on plant, insect and their interaction

Also, **Rivero *et al.* (2003)** reported low polyphenol oxidase (PPO) activity of peroxidase (POX) at 35°C in tomatoes; it has been also reported that there is a substantial decrease in protease inhibitor activity in tomato at temperatures below 22°C. At elevated temperatures, the thickness of leaf trichomes normally rises (**Bickford, 2016**).

In alfalfa (*Medicago sativa*), the concentrations of plant secondary metabolites (sapogenins and saponins) were elevated at increased temperatures, suppressing the growth of caterpillar (*Spodoptera exigua*). By contrast, the Green-veined butterfly, *Pieris napi* reacted to warming-mediated poor-quality foliage in Brassicaceae, by consuming significantly higher amounts of plant tissue. However, when fed on oilseed rape plants subjected to different temperatures with nutritional quality variations, the production of aphids (*Myzus persicae* and *Brevicoryne brassicae*) was not affected. Moreover, temperature-induced tobacco shifts (*Nicotiana tabacum*) have an impact on the tobacco hornworm, *Manduca sexta* that the normally accepted law of temperature size, which predicts an improved final mass of ectotherms (e.g. insects) at lower temperature, has been reversed.

Elevated Carbon Dioxide Levels

Photosynthesis, the primary physiological process in plants that converts sunlight into sugars and starch through the utilization of water and CO_2, plays a critical role in determining crop yield. The CO_2 required for photosynthesis enters the plant through stomatal openings found primarily on leaves, with less presence on stems. Elevated CO_2 concentrations (ECC) result in a faster acquisition and assimilation of carbon, promoting rapid growth and development of the plant (Fig. 2) (**Holley, 2022**). According to a comprehensive review by **Kimball *et al*. (1983)**, of over 400 observations, a significant increase in yield was observed in C_3 plants under doubled ambient CO_2 concentrations (ACC), which was 340 ppm at the time of the review (Fig. 2). When C_3 plants were exposed to ECC (from ambient 353 ppm to elevated 550 ppm) and supplied with adequate water and nutrients, **Kimball *et al*. (2016)**, reported an increase in yield of up to 19%, reinforcing previous findings that crop yield will increase under ECC. However, the literature suggests conflicting results for C_4 plants (such as maize) under ECC, with some studies reporting positive results. Additionally, ECC leads to an increased photosynthetic rate in plants due to reduced transpiration (**Wang *et al*., 2022**) and stomatal conductance (up to 19%–22%), thus decreasing crop evapotranspiration (ET) by up to 10% and increasing water-use efficiency. This reduction in ET may improve the drought tolerance of crops, particularly C_4 plants, as evidenced by a 41% increase in average yield in free-air carbon dioxide enrichment (FACE)-maize experiments. While ECC may offer potential benefits to crop productivity, a significant body of literature suggests negative impacts on food and nutrition quality (**Zhu *et al*., 2018**). These negative impacts include reduced protein concentrations [ranging from −15% to −9.8% in barley, potato, rice, and wheat), reduced mineral concentrations (averaging 8%), and vitamins (Fig. 1) ranging from −30% to −13% in rice; 50]. The combined effects of reduced food and nutritional quality, along with reduced crop yield, may threaten the food security of billions of people globally under the influence of climate change and ECC (**Zhu *et al*., 2018**).

Higher concentrations of CO_2 with the rise in temperatures in the atmosphere have direct effects on plant metabolism and affect the distribution, abundance and productivity of insects that feed on plants. The behaviour of phloem-feeding insects, when supplied with plants grown under increased CO_2, increases compared to leaf chewing insects. When leaf chewing insects like grasshoppers and caterpillar larvae feed on plants that are grown under higher CO_2 levels, more leaf area is eaten than they actually eat (**Harthik *et al*., 2021**). *Spodoptera litura* has been reported to grow under higher levels of CO_2 as a serious pest. The larvae of *Helicoverpa,* grown under high CO_2 ate much more leaf tissue than those under ambient CO_2. However, under elevated CO_2, adult moths increased and lived longer and laid considerably few eggs.

The change in CO_2 concentration also influences the plant biochemistry, along with the synthesis of secondary metabolites. The higher concentration of CO_2 is subjected to increased ratio of carbon to nitrogen in plants. Insects are allowed to consume more in order to achieve sufficient dietary nitrogen, resulting in slower larval growth and increased mortality. Phytophagous insects can become more susceptible to changes in atmospheric CO_2 concentration by CO_2 cascading effects on plant biochemistry, as certain plant feeding insect species produce their pheromone molecules on the basis of compounds taken from the host plants. Example: Bark beetles use the mevalonate pathway to generate pheromones, where certain components of aggregation pheromones originate from the hydroxylation of secondary metabolites derived from tree. Besides affecting the plant biochemistry, along with the synthesis of secondary metabolites changes in CO_2 concentration could also affect the plant yield. Example: estimated a yield loss in wheat, maize and cotton of 36 to 40 per cent in a scenario of low CO_2 emissions, and between 63 to 70 percent in a scenario of high CO_2 emissions.

Water Availability

Water availability is considered one of the significant factors affecting crop production and a threat to global food security. The changing climate strongly influences many processes, including precipitation, soil moisture, and evaporation. Rainfall is the primary water source for about 80% of the total crop production around the globe hence any disturbances in the rainfall pattern will have devastating consequences for global food production (Table 2). Furthermore, a substantial body of research suggests that the global hydrological cycle will be amplified under climate change, mainly due to temperature rise. However, because precipitation is only one of the many factors, other than the frequency and intensity of weather events, affecting global crop production, the impact of amplified global hydrological cycles on global crop production is yet to be fully understood. **Thornton *et al*. (2014),** review reported an increase in aridity from 17% to 27% from pre-industrial times to the dawn of the 21st century. Climate change has impacted not only precipitation but also ET, thereby increasing the water demand for irrigation. According to recent reports, by the end of the 21st century, irrigation requirements for crops could rise by 5%–20% due to global warming (**Subedi *et al*., 2023**). Additional factors that could impact water availability due to climate change are changes in surface runoff, stream flow, and water distribution through space and time. With changing climate, water availability for crop production will also be strongly limited due to increased freshwater demand for other societal needs, including urban and industrial ones.

More frequent and extreme precipitation events during climate change are expected to have detrimental effects on the population of insect pests. It is one of the weather factor that acts upon the activities of several insects by means of soil moisture or directly when exposed. Increased summer rainfall encourages a rapid rise in the soil dwelling wireworms, *Agriotes lineatus* population and larvae of root chewing insects, *Agriotes lineatus* (**Harthik *et al*., 2021**). Soil moisture kills insects by means of submerging in water, or affects the soil texture by preventing the emergence of insects. It is also harmful mainly to the insects that are free living in the soil as eggs or as newly-hatched larvae or nymphs.

The effect of the intense raindrops or water in the leaf axils will dislodge or drown small insects such as aphids, or newly-hatched larvae or nymphs from the plants. High proportions of cabbageworm young larvae, *Pieris rapae* and diamondback moth, *Plutella xylostella* on cabbage, are killed by high precipitation. Intense precipitation also has a catastrophic effect on the boring insect eggs and newly-hatched larvae such as the European corn borer, *Ostrinia nubilalis*, before boring into the plants. It also destroys aestivating adults of the black cutworm larva, *Agrotis ipsilon* and results in drowning of larvae in low-lying areas. Changes in pattern of rainfall are tracked by desert locust, *Schistocerca gregaria* migratory patterns in Sub-Saharan Africa. Precipitation also has a positive association with plant height, total area of the leaves, number of plants and number of leaves, nitrogen and chlorophyll content of the leaves, which has a direct or indirect impact on the population of insect pests.

Table 2. Yield reduction of various crops under water deficit from studies published after 2015 (adapted from Dietz *et al*., 2021).

Crop	Location	Climate	Response parameter	Mean yield		Experiment site
				Ambient	Drought stressed	
Oat			Grain (g m^{-2})	633	403	Greenhouse
Mandarin orange	India	Subtropical	Fruit (g)	148.2	115.3	Field
Cucumber	United Arab Emirates	Tropical and Subtropical desert	Fruit (g)	131.9	106.3	Greenhouse
Strawberry	Turkey	Dry-summer subtropical	Fruit (kg m^{-2})	5.38	1.96	Greenhouse
Mango	Pakistan	Tropical and subtropical desert	Fruit (kg $Plant^{-1}$)	64.3	33.6	Field
Tomato	Kenya	Marine west coast	Fruit (g $Plant^{-1}$)	574.7	466.3	Field
Common bean	South Africa	humid subtropical	Dry bean (t ha^{-1})	3.2	1.8	Field
Tomato	Kenya	Marine west coast	Fruit (g $Plant^{-1}$)	574.7	466.3	Field
Perennial ryegrass	Switzerland	Temperate oceanic	Aboveground biomass (t ha^{-1})	1.5	0.52	Field

Climate Change Effects on Agricultural Insect Pests

Elevated temperatures

Modern agricultural practices and scientific inquiry are centered on the ramifications of climate change, including elevated temperatures, rising CO_2 concentrations, floods, droughts, and more severe weather patterns (**Skendžić *et al*., 2021**). Climate change and weather anomalies impact insect pests, a major biotic factor, and directly and indirectly affect crops. Climate change directly affects the reproduction, development, survival, and dispersal of pests and indirectly impacts the interactions between and within insect species, including predators, competitors, and mutualists, and interactions with their environment. Insects, being poikilothermic, are significantly impacted by temperature changes. Temperature influences insect behavior, distribution, development, and reproduction. Temperature fluctuations greatly impact insect physiology, doubling their metabolic rate for each 10-degree Celsius increase. Elevated temperatures increase the feeding, performance, and dispersal of insects, potentially altering population dynamics. The temperature influences pest population and dynamics by affecting metabolism, metamorphosis, mobility, and host availability. Global warming could increase insect populations, resulting in earlier infestations and crop damage. Optimal temperatures for many insect pests could increase pest infestations under global warming scenarios. However, a uniform increase in pest abundance and crop losses is not guaranteed due to varying needs, tolerances, and temperature effects among insects. **Lehmann *et al*. (2020)** found a mix of responses among insect pests to climate warming, with most case studies indicating increased pest severity. One of the most notable impacts of altered temperatures on insect pests is their change in distribution and abundance. For example, a positive correlation exists between increased whitefly populations and high temperature and humidity (**Pathania *et al*., 2020**). Additionally, increased temperature affects the frequency, severity, and extent of bark and wood-boring insect outbreaks. For instance, recent warming has accelerated the development rate and decreased the overwinter mortality rate of the western pine beetle, leading to increased population growth during droughts (**Robbins *et al*., 2022**). Research suggests rising temperatures could lead to earlier emergence and longer insect life cycles. Insect pest host range shifts due to climate change are increasingly becoming common, which can greatly impact agricultural production. As an example of how global warming affects insects, it causes range expansion and increases overwinter survival in pests such as the corn earworm and the cotton bollworm, presenting major challenges to crop yield and pest control in maize, a significant food crop across the globe. These pests threaten the agricultural industry, as they can cause significant economic losses in crop yield and pest management efforts. With the projected increase in temperatures, agronomic and scientific research needs to continue to study and address the impacts of climate change on insects and their impact on crops. Aphids' susceptibility to temperature changes is well documented. These insects, which have a small body size and rapid life cycle, can experience significant shifts in migration patterns due to temperature increases, leading to sudden outbreaks and significant economic losses in agriculture and forestry (**Wu *et al*., 2020**). The phenomenon of global warming has led to a rise in the overwinter survival rate of pests such as the corn earworm and cotton bollworm, which in turn has expanded their geographical distribution, posing significant difficulties in terms of agricultural productivity and pest control efforts (**Nayak *et al*., 2020**). Furthermore, rising temperatures can result in a shorter developmental time for some insects, increasing the number of generations per growing season.

Increased carbon dioxide levels

Over the past 50 years, a notable change in the atmospheric composition has been observed with a rise in atmospheric CO_2 levels. CO_2 is essential to photosynthesis, and its elevated levels can influence plant physiology. ECC leads to decreased water loss through transpiration, increased stomatal openings, and photosynthesis rates (Fig. 4) **(Skendžić *et al*., 2021)**. As CO_2 levels rise, the amount of carbohydrates in leaves also increases; however, the nitrogen levels decrease. ECC can alter plant nutrient levels, particularly protein, and thus impact plant defense mechanisms against insects (Fig. 4) **(Zhang *et al*., 2020)**. ECC reduces the accumulation of the defense hormone, jasmonic acid (JA), and enhances salicylic acid (SA) in plants. For instance, ECC has been shown to decrease tomato resistance to the cotton bollworm (*Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae)) by suppressing JA accumulation. ECC can impact the rate of food consumption, growth, fertility, and population size of insect pests. As an example, ECC improved the feeding and reproduction of the Japanese beetle (*Popillia japonica* Newman (Scarabaeidae: Coleoptera)) and western corn rootworm (*Diabrotica virgifera virgifera* (Coleoptera: Chrysomelidae)). Conversely, ECC reduces leaf nitrogen levels in peanuts and ramie, leading to increased food consumption and slower growth rate in insects such as the tobacco cutworm (*Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) and castor semi-looper (*Achaea janata* Linn. (Lepidoptera: Noctuidae)). ECC levels can impact a plant's susceptibility to insect pests, as evidenced by molecular resistance studies in lepidopteran insects, where increased resistance was observed in tobacco but decreased in melons (**Zhang *et al*., 2020**). In interactions between chickpea and the *H. armigera*, research has shown that damage caused by *H. armigera* is reduced at ECC levels, and the insect survival rate is also lower. ECC levels result in a reallocation of photoassimilates to defense metabolites, reducing the carbohydrate pool in plants and rendering them less appealing or even toxic to insect larvae. ECC can impact the presence, numbers, and function of insects

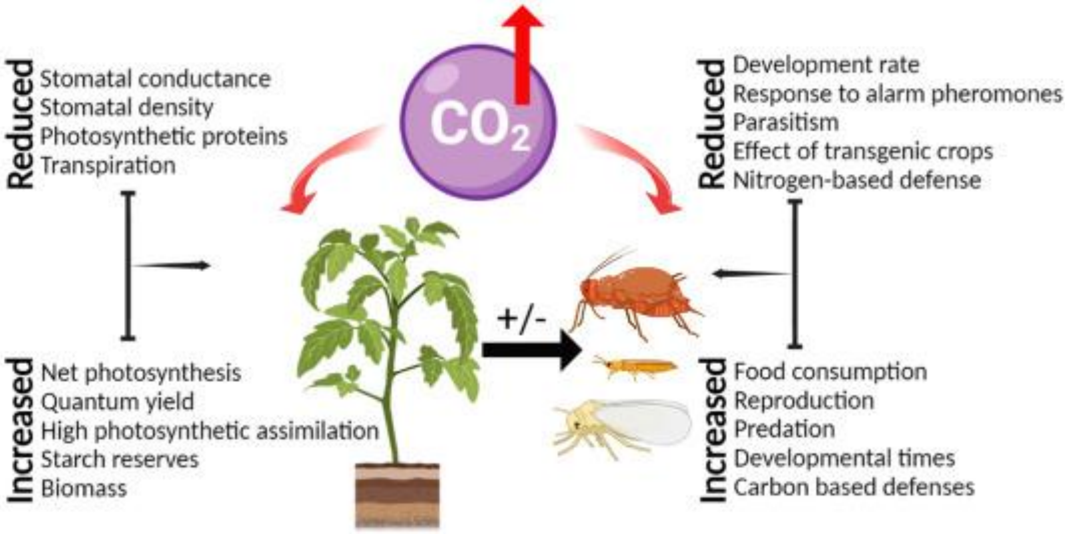

Fig. 4. Effect of elevated CO_2 on insect pest (Zhang *et al*., 2020)

that feed on plants. For example, ECC increases aphid abundance but does not affect the parasitism rate. ECC also reduces plant nutritional quality due to reduced nitrogen contents, leading to increased insect food consumption. Furthermore, ECC levels can influence pest behavior, as ECC has been observed to enhance aphid metabolic rate and feeding behavior. However, the impact of ECC on aphid development time is inconsistent, as it did not affect *Rhopalosiphum padi* L. (Hemiptera: Aphididae) reared on wheat but increased the development time of *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) reared on bell pepper. These changes may require alterations in crop management strategies, such as planting and harvest times, to avoid periods when pests are most active.

Changing precipitation

Changes in precipitation may lead to modifications in the quantitative, qualitative, and temporal characteristics of the precipitation events, thereby impacting precipitation regimes, soil water availability, atmospheric water vapor fluxes, and hydrological processes such as infiltration, evapotranspiration, and streamflow. The survival and reproduction of many insect pests are sensitive to changes in precipitation, leading to changes in their populations. Additionally, alterations in precipitation patterns can impact wireworm populations, leading to significant crop damage. Conversely, heavy rainfall can be beneficial, as it can wash away tiny pests such as aphids, mites, jassids, and whiteflies (**Pathak *et al*., 2012**). Alterations in precipitation can also impact the nutritional quality of plants consumed by herbivores, influencing their performance. Severe droughts can increase bark beetle populations, while moderately stressed trees may be more resistant to bark beetles. Additionally, research has shown that water stress on plants can lead to a decline in their biological processes, making them more susceptible to diseases and pests. Furthermore, studies have indicated that aphids raised on plants under water stress have a lower rate of parasitism due to the diminished size or availability of the host (**Ahmed *et al*., 2017**). Lastly, insect herbivores, such as sap-feeders, perform better when they feed on trees experiencing intermittent water stress than on constantly stressed trees.

Insects pests' distribution

Climate change effects on insect pests are well-documented, with temperature changes predicted to be particularly severe. These changes can directly affect the life-table parameters of insects, such as growth, reproduction, and survival, or indirectly impact factors, such as host effects, competition, and natural enemy pressure (**Frank, 2021**). Changes in precipitation levels also significantly affect insect pest biology and distribution, impacting global crop production. As a result of global warming, insects are projected to move toward the poles and higher elevations, increasing the risk of crop loss, for example, migratory locusts. The migrations of pests that harm crops will be significantly influenced by climate change, with temperature and precipitation playing critical roles (**Peng *et al*., 2020**), for example, rainfall pattern modifications linked with desert locust outbreaks in East Africa. While the frequency of outbreaks may be reduced by water-limitations, the anticipated rise in extreme weather events, including rainfall, could result in unprecedented outbreaks occurring in new regions. The expansion of the migration range of the *Agrotis ipsilon* moth was tied to increasing temperature in China (**Zeng *et al*., 2020**), accompanied by alterations in the species' lifecycle timing and an increased breadth of overwintering areas, which is a response to elevated winter temperatures. However, climate change impacts on insect pests are highly context-dependent, with some regions experiencing an increased number of generations while others experiencing a decrease. For instance, *Icerya aegyptiaca* (Douglas) (Hemiptera: Coccoidea: Monophlebidae) is expected to have a greater habitable area in Africa, South America, and Asia, while *I. purchase* Mask (Hemiptera: Coccoidea: Monophlebidae) is predicted to dominate South America, Asia, and Europe (**Liu and Shi, 2020**).

Meanwhile, the South American Tomato Pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), is expected to have negative impacts near the equator but positive impacts near the poles. The corn leafhopper, *Dalbulus maidis* (DeLong) (Homoptera: Cicadellidae), a major vector of maize crop diseases, is predicted to experience a reduction in suitable habitat in its native range (e.g., Brazil) but could pose a significant threat due to range expansion in continental African countries. Ultimately, climate change is expected to exacerbate the impacts of geographic ranges of pest populations, leading to reduced crop production and food security.

Overwintering survival

Insects, as poikilothermic organisms, are susceptible to seasonal variations in climate, particularly temperature (**Naeem-Ullah *et al*., 2020**). Cold temperatures pose a significant challenge to insects, impacting their physiological pro6cesses and causing mortality. To mitigate the effects of low temperatures, insects have evolved overwintering strategies, such as diapause, which reduces their physiological activity to tolerate cold temperatures, or freeze avoidance, where they eliminate potential nucleators to prevent freezing. Diapause is a crucial aspect of the insect life cycle and survival, being obligate for insects that produce one brood annually and facultative for multivoltine species that produce multiple broods. Environmental cues, such as photoperiod or day length, play a major role in inducing diapause, with short day lengths typically signaling harsh winter conditions (**Numata and Shintani, 2023**).

However, climate change is disrupting insect overwintering strategies by altering photoperiod through changes in temperature and precipitation, resulting in distorted diapause timing and an increased risk of extreme cold temperatures if insects enter diapause late in their life cycle (**Richards, 2020**). For instance, adult green stinkbugs in northern Japan can overwinter if they enter diapause in the previous season, but their nymphal stage during the winter season results in their death. In contrast, extended growing duration in the southern regions allows insects to reach adulthood before winter. Furthermore, entering diapause too early can also be detrimental to insects due to excessive energy drain can disrupt the entire ecosystem and negatively impact crop productivity (**Tougeron *et al*., 2020**).

Impact of Climate Change on Insects, Plants and Their Interactions

Climate change has significant consequences in every field of agriculture. Climatic changes like temperature, precipitation, humidity and other meteorological components influence the relationship between insect pests and plants. Climate change has enhanced the pest population and their damage potential by increasing the distribution, improving survival rates and developing the adaptability of insect pests. The change in population, mobility, and insect pest behaviour is caused by increasing temperatures, changed precipitation patterns and disrupted gaseous composition of the atmosphere etc. A number of variables that decide how much plants can grow are influenced by climate change. At the same time, incidence of higher temperatures, decline in the supply of water and changes in soil conditions would actually make it harder for plants to flourish. The relationships between plants and insects are altered by increased CO_2 and temperature, with important consequences for food security. Via warming acceleration of plant phenology creates mismatches between plants and insect pollinators. Likewise, changing the development rate of plant in relation to the development of insect can intensify/mitigate the effects of herbivore.

Impact of Climate Change on Insect Pests

The insect pests are seriously affected by overall rise in global average temperatures, weather pattern changes and severe climatic events. With these seasonal and long term changes the population dynamics of many insect pests would be influenced. Different climate patterns primarily affect insect ecosystems and their survival strategies. Significant climate change drivers like higher temperatures and CO_2 levels and lower soil humidity, have an effect on the nature of population of insect pests and results in subsequent crop losses. Abiotic parameters impose direct effects on the rate of distribution and abundance of insect pest populations by adjusting their growth, survival, reproductivity, dispersal and number of generations per season. Because of the rapid climate change, insect pests are developing increased overwintering stages and number of generations with rapid population growth. Temperature is said to cause direct effects among the abiotic factors. For example, increasing temperatures, from 1.5 to 2.5°C, will surely increase the winter survival and prolong the range of pink bollworm, *Pectinophora gossypiella* . During extended periods of drought, followed by heavy rainfall oriental armyworm, *Mythimna separata*, the populations raises due to the undesirable effects of drought on the activity and abundance of natural enemies of this insect pest.

Impact of Climate Change on Beneficial Insects

Climate change impacts the insect pest's natural enemies in a wide variety of ways. Plants grown under higher temperatures and CO_2 and lower precipitation provides various nutritional opportunities for different insect pests, eventually affecting the fitness of insect pest-feeding predators and parasitoids. Despite of a wide variety of host and parasitoid species, variability in precipitation is the key cause for differences in caterpillar parasitism. Parasitism of mealy bug is reduced under conditions of water stress combined with dry conditions in cassava, *Manihot esculenta* (**Harthik *et al*., 2021**). In relation to herbivore hosts and their movement, natural enemies locate their hosts based on their tolerance to environmental extremes. Predatory bugs, *Oechalia schellenbergii* were found to be more effective in destroying the cotton bollworm larvae when pea plants are cultivated at high CO_2 levels. Similarly, in feeding upon the aphid, *Aphis gossypii*, the coccinellid predator, *Leis axyridis*, was found to be more successful at higher CO_2 levels.

In hot summers rather than in moderate summers, ladybird beetles (*Coccinella septempunctata*) reduce aphid populations (*Sitobion avenae*) more effectively. Rise in temperature affects the production and release of volatile compounds and extra floral nectar by plants. These secretions help the insects to avoid the attack from natural enemies. Natural enemies need to undergo climate change for breeding purposes, after overcoming temperature extremes; they need to find hosts efficiently through a broad spectrum of temperature and humidity environments. *Trichogramma carverae*, the egg parasitoid fails to recognise hosts at temperature above 35°C and reduces fertility at 30°C. Some parasitoids evolve earlier than hosts in rapid response to temperature and often engage in the extinction of the parasitoid population in absence of the hosts. At elevated temperatures, the rate of insect parasitism will be reduced as host species emerge and move through the susceptible stages quickly before the appearance of parasitoids. Mild winters in temperate regions enhance the survival of parasitoids. Ex: Aphid parasitoids from cereal crops become active during winter and reduce spring aphid populations. The foraging behaviour of ants is often affected by temperature. In general, chemically recruited ants prefer to eat at temperatures lower than those that do not. As a consequence, increased temperature results in pheromone decay changing the trail following action which is disadvantageous to the activity of ant feeding. Hymenopteran parasitoids and small predators sometimes have a negative impact on rising temperatures. Ex: At 40°C BPH is 17 times more tolerant than its natural enemies *Cyrtorhinus lividipennis* and spider, *Pardosa pseudoannulata*.

Managing Agricultural Pest Infestations under Climate Change

Adaptation to the effects of climate change is a continual process that involves implementing strategies that manage and reduce the risks of climate change. Climate change is anticipated to cause more unpredictable pest outbreaks and increase their geographical range. The influence of a changing climate on crop yields is unclear, and the connection between insects and plants within ecosystems is poorly understood. Biological, economic, and sociological factors will impact the adaptability of agricultural farming. Furthermore, the physical, social, and financial resources of neighboring communities will determine their capacity to modify their pest management methods. Skyrocketing global trading and climate change are projected to amplify native and invasive pest frequency, making it increasingly important to have a quick adaptive ability to biotic (pest) and abiotic (climate change) pressures (**Zayan, 2019**). Therefore, prospective measures for adjusting to new pests and diseases and alleviating the adverse effects of current ones have been recommended. These measures comprise adjusted IPM methodologies, monitoring of climate and insect pests, and utilization of prognostic modeling instruments.

Approach of Modified Integrated Pest Management

Modified IPM is a critical approach to address the challenges posed by changing climate on agricultural insect pests. Climate change can cause shifts in insect pests' distribution, abundance, and phenology, thereby affecting crop yields. In response to these changes, traditional pest management strategies may become less effective, making it necessary to modify and integrate new tactics into the existing IPM approach. IPM is an eco-friendly and sustainable pest management approach that integrates multiple strategies to minimize pest damage while reducing environmental impact and dependence on chemical insecticides (**Dara, 2019**). However, with the increasing variability in climate patterns, the traditional IPM approach must be adjusted to account for the changing risks and uncertainties associated with insect pest management.

One of the strategies to modify IPM under climate change is adjusting crop planting timing according to the climatic trends. Conducting a thorough analysis of the local climate trends, including temperature, precipitation, and pest occurrences will help identify the specific climate-related challenges that a region is facing. Additionally, crop varieties should be selected that are better suited to the changing climate and can withstand potential pest pressures. Some crop varieties may be more resilient to extreme temperatures or have natural resistance to certain pests. Developing a flexible planting calendar that considers the changing climate patterns and pest life cycles, for example, planting crops earlier or later in the season can reduce exposure to pest outbreaks, as it aligns with changes in the phenology of insect pests. Additionally, planting different crop varieties with greater resistance to insect pests can reduce the risk of crop loss (**Dara, 2019**).

Another strategy to modify IPM is to increase biodiversity at field margins. Changing climate can nullify the efforts of crop protection strategies. For example, plants under stress due to factors such as drought may not be able to handle the pest pressure. Increasing the number of natural enemies can help to control insect pest populations and reduce the need for chemical insecticides. For example, research has shown that integrating diverse crop rotations, intercropping, and increasing floral diversity in agroecosystems can reduce insect pest damage and increase beneficial insects, such as pollinators and predators (**Komala *et al*., 2021**). In agricultural landscapes, the dynamics between pests, beneficial organisms, and crops are inherently intricate. Introducing biodiversity at field margins taps into the ecological principles of trophic interactions and symbiotic relationships to foster natural pest control mechanisms. This multifaceted approach encourages a deeper understanding of the intricate web of relationships within agroecosystems, paving the way for more effective IPM implementation. A key aspect of the modified IPM strategy is the deliberate augmentation of natural enemies to regulate insect pest populations. By providing shelter, food sources, and breeding grounds through diverse crop rotations, intercropping, and floral enrichment, beneficial insects such as pollinators and predators can thrive and exert their regulatory effects on pest populations. This concept not only reduces reliance on chemical insecticides but also promotes long-term pest management stability.

Incorporating pheromones and allelochemicals is a vital element of IPM practices, encompassing biocontrol, mating disturbance, push-pull tactics, surveillance, and entrapment. However, with changing climate, the efficacy of these compounds is expected to decline, making it necessary to modify the application of these tools (**El-Sayed *et al*., 2021**). For example, the volatility of pheromones and allelochemicals may decrease under high-temperature conditions, requiring a synergist or adjuvant to maintain their effectiveness.

Likewise, biopesticides that are based on living organisms, such as viruses, fungi, bacteria, and nematodes that are pathogenic to insects, are vulnerable to alterations in the environment. Thus, it is anticipated that the effectiveness of these management techniques and synthetic insecticides will decrease as temperature increases and relative humidity decreases. Therefore, it is crucial to concentrate on creating innovative approaches for controlling pests and exploring new formulations of pest management products. For example, **Wenda-Piesik *et al*. (2016)**, evaluated the repellent and attractive qualities of eco-friendly volatile organic compounds (VOCs) at different concentrations on confused flour beetles (*Tribolium confusum* Du Val (Coleoptera: Tenebrionidae)). The study found that the highest concentration of applied volatile organic compounds significantly repels individuals of the species in question (**Piesik *et al*., 2016**). This research lays the foundation for creating new eco-friendly and sustainable pest control methods.

Community involvement is crucial for successful pest management. Farmers, agricultural experts, researchers, and policymakers must collaborate to share knowledge, experience, and best practices. Local communities should be encouraged to participate in monitoring pest populations, reporting outbreaks, and implementing control measures. Training programs and extension services can be vital in disseminating information about climate-smart pest management techniques. Engaging with farmers through workshops, field days, and demonstration plots can enhance their understanding and adoption of sustainable practices.

The changing climate poses new challenges for agricultural insect pest management. Traditional IPM may become less effective in a changing climate, making it necessary to modify and integrate new tactics. Modifying the timing of crop planting, increasing biodiversity at field margins, adjusting the use of pheromones and allelochemicals, and developing new pest management strategies are some of the critical strategies to mitigate the impacts of agricultural insect pest under changing climate (**Gvozdenac *et al*., 2022**). To maximize the impact of these strategies, it is crucial to gain a deeper understanding of how climate change impacts the efficacy of various synthetic insecticides, the duration of their presence in the environment, and the growth of resistance to certain insecticides among pest populations.

Pest monitoring

Monitoring agricultural pests has been identified as a key strategy for controlling insect pests under changing climate conditions. The first step in managing agricultural pests is accurately identifying them and their population levels. This information is critical for effective decision-making and developing IPM strategies. Monitoring is, therefore, an important component of IPM, providing a basis for assessing the status of pests and the impact of management interventions. Climate change can increase the likelihood of new pest introductions and alter the distribution and abundance of existing pests. Regular monitoring can help detect changes in pest populations, which in turn can inform the development of more effective IPM strategies (**Singh *et al*., 2023**).

Various methods for monitoring agricultural pests include direct observation, trapping, and remote sensing . Direct observation involves visually examining crops and surrounding areas for signs of pest damage and the presence of pests. This method is particularly useful for monitoring visible pests, such as caterpillars and aphids. Trapping, on the other hand, involves using baited traps to attract pests and monitor their populations. This method is especially useful for pests that are difficult to observe, such as moths and beetles. Finally, remote sensing, including aerial and satellite imagery, can provide a broader perspective on pest populations and their distribution and the impact of management interventions (**Klein *et al*., 2021**).

One example of monitoring in pest management is the study by **Yang *et al*. (2017)**. In this study, aphid species damage has been determined by mapping the Mississippi River delta. The use of remote sensing technology has allowed for predicting the most likely locations where aphids may attack wheat crops. To improve pest management, it is critical to have a clear understanding of the situation, including insect damage levels, weed infestations, and plant diseases. Remote sensing technology provides crucial data for decision-making in various pest management programs and helps monitor insect populations accurately, leading to improved pest control and reduced management costs. IPM strategies rely on forecasting pest outbreaks and providing early warnings to manage pests and minimize crop loss and cultivation costs. Remote sensing techniques aid in detecting crop stress, pest infestations, disease development, and monitoring drought, with improved spatial and temporal resolution compared to traditional monitoring methods. Integrating remote sensing with Global Positioning System (GPS) and Geographic Information System (GIS) technologies, such as aerial videography, enhances decision-making by agricultural consultants. Studies have been conducted to evaluate the effectiveness of remote sensing in IPM, including the use of volunteered geographic information (VGI) and mobile phone reports from farmers (**Yan *et al*., 2017**), offering unique benefits for targeted pest management.

The examples of monitoring in pest management discussed in this review highlight the importance of regular monitoring in developing effective pest management strategies and managing insect pests under changing climate conditions, as the effects of climate change continue to impact global agriculture. With the increasing unpredictability of pest infestations and their expanding geographic range, quickly adapting to changing conditions becomes crucial. Furthermore, using climatic models can help reduce the uncertainty surrounding crop yields and insect-plant interactions in ecosystems. By providing valuable insights into the behavior of insect pests, climate forecasting, and climatic models can potentially improve the overall efficiency and effectiveness of pest management practices. By embracing this technology and integrating it into their decision-making processes, farmers and other stakeholders can take proactive measures to mitigate the risks posed by agricultural insect pests in a changing climate.

Conclusion

In modern era climate change is globally acknowledged fact. It has a serious effect on the diversity, distribution, occurrence, reproduction, development, growth, voltisim and phenology of insect pests and plant species. It also affects the activity of plant defence and resistance system, invasive insect species, natural enemies, pollinators and insect pest management strategies. Food protection in the 21st century will be the greatest challenge for humanity in the years to come, considering the declining efficiency of production due to the depletion of the natural resource base, the drastic effects of climate change on the diversity and abundance of insect pests, and the scale of crop losses. Coping with climate change is very tedious, due to its uncertainty, ambiguity, unpredictability and differential effects over time and place. It is important and challenging in agriculture to understand abiotic stress reactions in plants, insect pests, invasive insect species, natural enemies and pollinators. Integrated Pest Management (IPM) strategies, combining cultural, biological, and chemical methods, should be employed to minimize reliance on pesticides and reduce environmental impact. Forecasting systems based on historical records, remote sensing data, and citizen science reports can provide early warnings and aid in pest outbreak mitigation. Developing pest-resistant crop varieties and drought-resistant crops can enhance food security and reduce reliance on chemical controls. Insurance programs and financial tools help farmers manage risks and invest in pest management strategies. Educating and engaging farmers, communities, and stakeholders is crucial for effective pest management. By implementing these recommendations, we can reduce the risk of crop damage, improve food security, and safeguard agriculture in a changing climate.

The effects of climate change on crop production, mediated by changes in populations of extreme insect pests, should be carefully considered in the planning and implementation of adaptation and mitigation strategies for future pest management programmes. It is then vital to look at the possible impacts of climate change on crop safety in a concerted manner and to establish effective actions to mitigate the impacts of climate change on food security.

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تأثير عوامل التغير المناخي المختلفة على الآفات الحشرية الزراعية وإنتاج المحاصيل واستراتيجية إداراتها فى الهند - دراسة مرجعية

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في الختام، تشكل الآفات الحشرية الزراعية تهديدا كبيرا للأمن الغذائي، وخاصة في مواجهة تغير المناخ. ولمعالجة هذه المشكلة، يجب تنفيذ استراتيجيات الإدارة الفعالة. أصبح تغير المناخ حقيقة معترف بها عالميًا. وله تأثير خطير على تنوع وتوزيع ووجود وتكاثر وتطور ونمو وفينولوجيا الآفات الحشرية والأنواع النباتية. كما أنه يؤثر على نشاط نظام الدفاع والمقاومة النباتية وأنواع الحشرات الغازية والأعداء الطبيعيين والملقحات واستراتيجيات إدارة الآفات الحشرية. ستكون حماية الغذاء في القرن الحادي والعشرين التحدي الأكبر للبشرية في السنوات القادمة، بالنظر إلى انخفاض كفاءة الإنتاج بسبب استنفاد قاعدة الموارد الطبيعية، والآثار الجذرية لتغير المناخ على تنوع ووفرة الآفات الحشرية، وحجم خسائر المحاصيل. إن فهم بيولوجيا وسلوك الآفات فيما يتعلق بالبيئة أمر بالغ الأهمية، لأن تغير المناخ سيغير توزيعها وسلوكها. يعد رصد التغيرات في أعداد الآفات من خلال الأساليب التقليدية وتقنيات الاستشعار عن بعد والمبادرات العلمية للمواطنين أمرًا ضروريًا للتدخل في الوقت المناسب. وينبغي استخدام استراتيجيات الإدارة المتكاملة للآفات، التي تجمع بين الأساليب الثقافية والبيولوجية والكيميائية، لتقليل الاعتماد على المبيدات الحشرية وتقليل التأثير البيئي. يمكن لأنظمة التنبؤ المستندة إلى السجلات التاريخية وبيانات الاستشعار عن بعد والتقارير العلمية للمواطنين أن توفر إنذارات مبكرة وتساعد في التخفيف من تفشي الآفات. إن تطوير أصناف المحاصيل المقاومة للآفات والمحاصيل المقاومة للجفاف يمكن أن يعزز الأمن الغذائي ويقلل الاعتماد على الضوابط الكيميائية. إن التعامل مع تغير المناخ أمر شاق للغاية، بسبب عدم اليقين والغموض وعدم القدرة على التنبؤ وآثاره المتباينة بمرور الوقت والمكان. من المهم والصعب في الزراعة فهم تفاعلات الإجهاد اللاأحيائي في النباتات والآفات الحشرية وأنواع الحشرات الغازية والأعداء الطبيعيين والملقحات. ينبغي دراسة تأثيرات تغير المناخ على إنتاج المحاصيل، والتي تتوسطها التغيرات في أعداد الآفات الحشرية الشديدة، بعناية عند تخطيط وتنفيذ استراتيجيات التكيف والتخفيف من آثار برامج إدارة الآفات المستقبلية . ومن الضروري إذن النظر في التأثيرات المحتملة لتغير المناخ على سلامة المحاصيل بطريقة منسقة ووضع إجراءات فعالة للتخفيف من آثار تغير المناخ على الأمن الغذائي. تساعد برامج التأمين والأدوات المالية المزارعين على إدارة المخاطر والاستثمار في استراتيجيات إدارة الآفات. يعد تثقيف وإشراك المزارعين والمجتمعات وأصحاب المصلحة أمرًا بالغ الأهمية للإدارة الفعالة للآفات. ومن خلال تنفيذ هذه التوصيات، يمكننا تقليل مخاطر تلف المحاصيل، وتحسين الأمن الغذائي، وحماية الزراعة في مناخ متغير.

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