Safeguarding Tomato Cultivation: Challenges and Integrated Pest Management Strategies in North India

Harsh Khokhar[1] and Chitranjan Kumar[1]*

[1]Amity Institute of Organic Agriculture, Amity University Uttar Pradesh, Noida, India
*Corresponding author email: ckumar@amity.edu; https://orcid.org/0000-0002-9003-6300

Abstract. Tomato (Solanum lycopersicum L.), crucial for global nutritional security, faces pests and diseases, leading to excessive use of chemical pesticides by farmers due to climate variability and cropping patterns.Integrated pest management (IPM) practices can help reduce over-reliance on pesticides and align with Good Agriculture Practices (GAP) standards. Understanding the distribution, prevalence, and factors influencing insect pest severity is crucial for developing tailored management strategies. IPM is becoming an emerging sustainable approach to pest management, utilizing viable strategies such as biological control, cultural practices, host plant resistance, and mechanical/physical control measures; however, challenges like limited farmer knowledge and resources hinder widespread adoption. Climate change and extreme weather events are causing significant impacts on crop production and agricultural pests, particularly in small-scale farms. These changes can expand insect range, increase overwintering survival, and increase the risk of invasive species and diseases. Implementing IPM in small-scale production requires adapting to different scales, identifying potential approaches, and addressing knowledge gaps. Integrated approaches, intercropping, cover cropping, and legume crop rotation are essential for developing agroecosystems and minimizing damage. Opportunities lie in digital technologies, precision agriculture, biotechnological innovations, and climate-resilient strategies. Strengthened farmer training, public-private collaborations, and informed decision-making are essential for IPM's success.

Keywords: Climate change, Insect-pests, IPM practices, North India, Nutritional security, Tomato

Significance: Climate change and extreme weather events are affecting crop production and agricultural pests, especially in small-scale farms. Implementing integrated pest management requires adapting to different scales, addressing knowledge gaps, and utilizing climate smart technologies, precision agriculture, and climate-resilient strategies

1. Introduction

Vegetables are pivotal in ensuring nutritional security worldwide, serving as vital sources of micronutrients, vitamins, and minerals. Among the myriad of commercially cultivated vegetable crops in India, the tomato (*Solanum lycopersicum* L.), originating from South America, commands a significant portion of both cultivation area and production. Tomato, renowned for its edible fruits and numerous cultivars, is a crucial "protective and remunerative vegetable" crop due to its exceptional nutritional and economic value [1]. Integral to Indian culinary traditions, the tomato is a treasure trove of vitamins A, B, C, potassium, minerals, and fibres [2]. Its versatility knows no bounds, finding application in diverse culinary creations such as soups, salads, pickles, ketchup, and sauces, while also serving as a staple vegetable in various cuisines worldwide. Notably, the presence of lycopene, a potent antioxidant, underscores the tomato's health-promoting properties, reducing the risk of ailments like prostate cancer [3]. Recognized as a crucial export commodity by the Agricultural and Processed Food Products Export Development Authority (APEDA), the tomato not only fulfils local demands but also contributes significantly to international markets.

Tomato cultivation faces a myriad of challenges, foremost among them being the relentless onslaught of insect pests that threaten the health and productivity of the crop. Tomato Fruit Borer (*Helicoverpa armigera*) represents a significant threat to tomato crops worldwide [4]. This highly adaptable pest, also known as the corn earworm or cotton bollworm, has a wide range of host plants, including tomatoes, corn, cotton, and various other crops. Native to the Old-World tropics and subtropics, this moth species has spread globally due to international trade and globalization. Australian agricultural species *Helicoverpa armigera* and *Helicoverpa punctigera* Wallengren face pest status due to physiological, behavioral, and ecological factors, necessitating effective regional approaches for research and management [5]. The adult moth lays eggs on tomato plants, typically on the fruit or nearby foliage [6]. Upon hatching, the larvae bore into the fruit, where they feed voraciously on the seeds and pulp. This feeding activity not only damages the fruit but also creates entry points for pathogens, leading to secondary infections and rot. Additionally, the presence of larvae in the fruit renders it unmarketable, causing economic losses for farmers. Tomato Fruit Borers exhibit a remarkable ability to develop resistance to insecticides, making chemical control challenging and often ineffective [7]. Furthermore, their nocturnal behaviour and cryptic colouration make them difficult to detect and manage using traditional methods. Integrated pest management (IPM) strategies that combine various control measures are therefore essential for effectively managing this pest. Overall, vigilance, proactive management strategies, and a multidisciplinary approach are crucial for effectively controlling Tomato Fruit Borers and safeguarding tomato crops against their destructive impact [8]. This review explores the implementation of Integrated Pest Management (IPM) in modern agriculture, focusing on strategies such as biological practices, cultural practices, host plant resistance, and chemical control. It examines case studies and success stories from various regions, addressing future directions and research needs to refine IPM's scope in response to changing agricultural landscapes and pest dynamics.

1.1 Plant pests and diseases

One of the most notorious adversaries is the tomato hornworm (*Manduca quinquemaculata*), the larval stage of the five-spotted hawkmoth [9]. These sizable caterpillars, identifiable by their vibrant green colouration and distinctive horn-like protrusion, devour tomato foliage with alarming voracity, often defoliating entire plants if left unchecked. This large caterpillar is renowned for its voracious appetite and its ability to inflict substantial damage to tomato crops if left unmanaged [10]. Adult tomato hornworm moths lay their eggs on the undersides of tomato plant leaves. Once hatched, the larvae emerge and begin feeding on the foliage, stems, and even the green fruits of the tomato plant. These caterpillars can grow to considerable sizes, reaching up to 4 inches in length. The feeding activity of tomato hornworms can cause extensive defoliation of tomato plants, leading to reduced photosynthesis and overall plant vigour. In severe infestations, they can completely strip the leaves from the plant, leaving it weakened and susceptible to other stresses or diseases. Additionally, tomato hornworms may also feed on the fruits, leaving behind unsightly damage and reducing marketability. Regular monitoring of tomato plants for signs of tomato hornworm infestation, such as chewed foliage or the presence of caterpillars, is essential for early detection and prompt intervention. Equally insidious are whiteflies (*Bemisia tabaci*), are typically found on the undersides of tomato leaves, where they congregate in large numbers. They pierce the leaf tissue with their needle-like mouthparts and extract sap, leading to yellowing, wilting, and distortion of the leaves [11]. The feeding activity of whiteflies weakens the plants, reducing their ability to photosynthesize and produce healthy fruits. Additionally, whiteflies secrete a sticky substance called honeydew, which promotes the growth of sooty mould, further impairing the plant's health. One of the most significant concerns associated with *B. tabaci* infestations in tomato crops is their ability to transmit plant viruses. Whiteflies can act as vectors for several devastating viruses, including Tomato yellow leaf curl virus (TYLCV) and Tomato chlorosis virus (ToCV) [12]. These viruses can cause severe symptoms in tomato plants, such as yellowing and curling of leaves, stunted growth, and reduced fruit quality and yield. Once infected, there are limited options for managing virus diseases in tomato crops, making prevention of whitefly infestations crucial. By implementing a comprehensive approach to whitefly management, tomato growers can effectively mitigate the damage caused by *B. tabaci* and protect their crops from yield losses and disease outbreaks.

1.2 Impact of plant pests and diseases on food security:

The 2007/2008 global food crisis led to food price spikes, hunger, and political unrest in the Middle East and Africa [13, 14]. The climate crisis is expected to disrupt food supply chains and increase plant diseases, resulting in lower crop yields and reduced food stockpiles. Plant diseases, such as

Fusarium oxysporum f. sp. cubense tropical race 4, causing panama disease of banana can impact food crop production and social and political stability [15]. Examples include the 19th-century Irish potato famine [16], the Bengal famine [17], and recent coffee rust outbreaks in Central America [18]. Emerging plant diseases can undercut agricultural productivity, undermining other investments in agriculture that alleviate hunger. Food security is essential for all people to have access to sufficient, safe, and nutritious food to meet their dietary needs and preferences. Policy discussions should consider the deleterious impacts of plant diseases on crop production to ensure food security.

1.3 Pests and viral borne diseases:

Aphids, small soft-bodied insects belonging to the Aphidoidea superfamily, are common pests that can afflict tomato plants. These tiny insects feed on the sap of tomato plants by piercing the plant tissues with their needle-like mouthparts. While aphids can infest various parts of the tomato plant, they are often found clustered on tender new growth, stems, and the undersides of leaves [19]. The presence of aphids on tomato plants can cause several detrimental effects. Firstly, aphids remove vital nutrients from the plant sap, leading to stunted growth, reduced vigour, and overall weakened plant health. Additionally, aphids excrete a sugary substance known as honeydew, which can attract ants and serve as a medium for the growth of sooty mould, further compromising the plant's photosynthetic abilities [20]. One of the most significant concerns associated with aphid infestations in tomato crops is their ability to transmit plant viruses. Aphids can act as vectors for various viruses, including Tomato yellow leaf curl virus (TYLCV) and Cucumber mosaic virus (CMV), among others [21]. These viruses can cause severe symptoms in tomato plants, such as leaf curling, yellowing, mottling, and reduced fruit quality and yield.

1.4 Leafmining insects:

Leafminers, belonging to the Liriomyza genus, are small fly larvae that represent a significant threat to tomato plants. These pests' tunnel through the leaves of tomato plants, leaving distinctive serpentine mines or trails as they feed. Leafminer infestations can lead to reduced photosynthesis, leaf damage, and ultimately diminished plant health and yield. The adult leafminer is a tiny fly that lays eggs on the undersides of tomato leaves. Once the eggs hatch, the larvae burrow into the leaf tissue, creating tunnels as they feed on the inner layers. This feeding activity weakens the leaves, causing them to become discolored, distorted, and in severe cases, to drop prematurely from the plant [22]. Additionally, the tunnels left behind provide entry points for pathogens, increasing the risk of secondary infections. Moreover, cutworms (Noctuidae family), nocturnal caterpillars that hide in the soil during the day, emerge at night to sever young tomato seedlings at the soil level, leading to wilting and death. Their damage is often mistaken for damping off disease, which complicates management efforts [23].

1.5 Piercing and sucking pests:

Another threat to tomato is Thrips, belonging to the Frankliniella genus, small, slender insects that pose a significant threat to tomato plants. These pests are known for their rasping-sucking mouthparts, which they use to pierce plant tissues and feed on the sap. Thrips infestations can cause various symptoms in tomato plants, including silvering or bronzing of leaves, distorted growth, and reduced fruit quality and yield. Thrips are typically found on the undersides of tomato leaves, where they congregate in large numbers. They feed by puncturing plant cells and sucking out the contents, leading to tissue damage and discoloration. Additionally, thrips may transmit plant viruses, such as Tomato spotted wilt virus (TSWV), which can cause severe symptoms in tomato plants, including necrotic lesions, leaf curling, and stunted growth [24].

Spider mites (Tetranychidae family), minuscule arachnids, present yet another challenge, piercing leaf cells and sucking out their contents, resulting in stippling, yellowing, and eventual browning of leaves. Their infestations thrive in hot, dry conditions, exacerbating the damage they inflict [25]. Integrated pest management (IPM) strategies that combine cultural practices, biological control agents, and judicious use of chemical pesticides are essential for mitigating the impact of these diverse and destructive insect pests on tomato crops. Regular monitoring, early intervention, and a holistic approach to pest management are imperative to safeguarding the health and productivity of tomato plants against these relentless adversaries.

2.0 Climate change impact on tomato pests and diseases:

Climate change has a significant impact on tomato disease severity, with various pathogens such as fungi, bacteria, and viruses affecting tomato growth. Tomato diseases can be caused by various factors such as temperature, CO_2 concentration, relative humidity, and other factors. Fungi like *Alternaria solani* [26], *Seporia lycopersici* [27], *Botrytis cinerea* [28], *Fusarium oxysporum* f. sp. Lycopersici [28], *Verticillium dahliae* [29], and *Phytoplasma solani* [30] increase with high relative humidity. Bacteria like *Clavibacter michiganensis* subsp. michiganensis [31] decrease at low temperatures and high temperatures, while *Phytoplasma solani* [32] increase with high relative humidity. Viruses like tomato spotted wilt virus [33], cucumber mosaic virus [34], tomato yellow leaf curl virus [35], Sardinia virus [36], tomato brown rugose fruit virus [37], tomato mosaic virus [38], paritaria mottle virus, [39] and pepino mosaic virus [40] increase with high temperatures and humidity. Vioids like tomato spindle tuber viroid [41] also decrease at low temperatures and increase with dry conditions. Overall, climate change has a significant impact on tomato disease severity and crop yield.

2.1 Distribution and prevalence of insect pests in North India

Tomato is among top three most valuable vegetables in India, after potato and onion. It is the country with the highest tomato cultivation and production, after China. Tomatoes are used in canned products, salad, ketchup, puree, sauces, and processed foods. However, tomato yield in India is affected by a range of insect pests, with the major pests being Leaf miner, Whitefly, Aphid, Fruit borer, and Jassid. The estimated losses to the tomato crop due to insect pest attacks range from 30-35%. It is crucial to know the time of insect pest infestation to use effective pest management practices. In North India, tomato cultivation is prevalent across various states, including Punjab, Haryana, Uttar Pradesh, Rajasthan, and others. The region's diverse agro-climatic conditions make it suitable for tomato cultivation, but it also makes it vulnerable to a range of insect pests. Here's a detailed overview of the major insect pests affecting tomato crops in North India [42, 43]:

compile pest details along with their causal relation with plant with references under one subheading

Tomato Fruit Borer (*H. armigera*):

Tomato Fruit Borer is a widespread pest in North India, particularly during the warmer months. It is prevalent in states like Punjab, Haryana, Uttar Pradesh, and Rajasthan, where tomato cultivation is extensive. Its infestations can cause significant damage to tomato crops, leading to yield losses if not effectively managed.

2.1.1 Whitefly (*B. tabaci*):

Whiteflies are a common pest in North India and can be found throughout the region, especially in areas with high humidity and temperatures. They are prevalent in states like Punjab, Haryana, and Uttar Pradesh, where tomato cultivation is widespread. Its infestations can lead to yellowing, wilting, and distortion of tomato leaves, affecting plant health and productivity. Whiteflies are a type of insect that feed on the juices of leaves, often found on wilted leaves. They can be found by brushing or shaking the leaves and examining the undersides for stationary immature insects. Whiteflies have a roof like body with vertically tilted wings. Their life cycle consists of females laying up to 150 eggs, which hatch in eight to ten days. The first instar nymphal stage is mobile, followed by four immature stages: second and third nymphs, and the last pupa. The active adult whitefly spreads the virus, taking 18-48 days in warm weather and 30-48 days in winter.

2.1.2 Aphids complex:

Aphids are ubiquitous pests in North India and can be found infesting tomato crops in various states. They thrive in temperate climates and are prevalent during the growing season, particularly in spring and early summer. Myzus persicae infestations can cause stunted growth, curling of leaves, and reduced fruit quality in tomato plants. Aphids, small insects that pierce plants, thrive in temperature extremes between 25-30°C. Thrips, also known as rasping-sucking insects, develop at their peak when temperatures are between 26.4-29°C and 8.4-12.6°C, with relative humidity ranging from 75-85%. North India experiences similar conditions, with temperatures ranging between 15-30°C positively influencing thrips' growth.

2.1.3 Leafminer (*Liriomyza* spp.):

Leaf miners are serious pests that attack crops, causing economic yield loss. They are small maggots with piercing mouthparts that damage leaf tissues, reducing photosynthesis and affecting crop quality. Their infestation can significantly affect growth and yield. Effective management requires timely detection and control measures to reduce their impact on crops. Leafminers are a common problem in North Indian tomato crops, especially during the warmer months. They are prevalent in states like Punjab, Haryana, and Uttar Pradesh, where tomato cultivation is extensive. *Liriomyza spp*. infestations can lead to the formation of characteristic serpentine mines on tomato leaves, affecting photosynthesis and overall plant health. Hamza et al. [44] tested four insecticides against leaf miner, with Spinetoram showing the highest reduction after 7 DOA, followed by Bifenthrin at 57%. Deltaphos was the least toxic. Integrated approaches are recommended for effective management.

2.1.4 Cutworms (*Agrotis* spp.):

Cutworms are sporadic pests in North Indian tomato crops, with outbreaks occurring periodically. They are prevalent in states with favorable conditions for their development, such as Punjab, Haryana, and Uttar Pradesh. Agrotis spp. larvae can sever young tomato seedlings at the soil level, causing wilting and death. Cutworms, a polyphagous pest, are a significant threat to agricultural crops, particularly during the seedling stage. They feed on leaves, stems, and tubers, causing significant damage. Chemical control is often ineffective due to their larval hiding behavior and active feeding at night. Biological control, such as entomopathogenic nematodes (EPNs), has become a pragmatic options. EPNs like

Steinernema spp. and *Heterorhabditis* spp. have shown significant potential in killing cutworms in soil, making them a viable alternative to chemical methods [45].

2.1.5 Thrips (*Frankliniella* spp.):

Thrips are widespread pests in North Indian tomato crops, prevalent throughout the growing season. They are found in various states, including Punjab, Haryana, Uttar Pradesh, and Rajasthan. Frankliniella spp. infestations can cause silvering or bronzing of tomato leaves, distorted growth, and reduced fruit quality and yield. *Thrips palmi* has been classified as a pest native to southern Asia, spreading to tropical and subtropical countries [46]. It has been observed on plants from 20 botanical families, including Cucurbitaceae, Solanaceae, and Orchidaceae. *T. palmi*, a pest causing damage to Orchidaceae flowers and fruits, is being controlled through phytosanitary measures, meeting all PLH Panel criteria for a Union quarantine pest [46].

In summary, the major insect pests of tomato crops in North India, including tomato fruit borer, whitefly, aphids, leafminer, cutworms, and thrips, are distributed throughout the region and can cause significant damage if not effectively managed through integrated pest management practices. Vigilance, regular monitoring, and timely intervention are essential for mitigating the impact of these pests on tomato cultivation in North India.

3.0 Economic implications of insect pest damage

The economic implications of insect pest damage to tomato crops can be significant, impacting both growers and consumers alike. Here's an overview of the economic consequences of various insect pest damage to tomato crops [47].

3.1 Reduction in yield:

Insect pests such as the tomato fruit borer, whitefly, aphids, and others can cause direct damage to tomato plants, leading to reduced yield. Infested fruits may be unmarketable or have reduced quality, resulting in lower market prices or rejection by buyers. Yield losses due to insect pest damage can translate into significant economic losses for growers, especially in regions where tomato cultivation is a major source of income. The study reveals that whitefly, a prevalent pest among tomato plants, causes significant crop loss. However, farmers in Tanzania's Arusha, Morogoro, and Iringa regions have varying knowledge of whitefly and control options, indicating a knowledge gap between their understanding and standard practices in controlling the pest [48].

3.2 Increased production costs:

Growers may incur additional expenses for pest management measures, including the purchase of insecticides, labour for scouting and application, and equipment for pest control. Chemical control measures, such as insecticide sprays, can be costly and may need to be applied multiple times throughout the growing season to manage pest populations effectively. Organic or alternative pest control methods may also entail higher labour costs or investment in specialized equipment, adding to production expenses. A small farm's definition is context-dependent, varying based on geographic location and farm enterprise type, such as extensive livestock production versus intensive vegetable production. This review discusses the underserved small-scale farm sector in developed economies, and highlights the importance of IPM practices in enhancing local food security. It highlights challenges and opportunities in implementing IPM in small-scale production, including adapting to different scales, identifying potential approaches not widely used, and addressing knowledge gaps and opportunities for IPM outreach to small-scale producers [49].

3.3 Decreased Marketability and Consumer Confidence:

Insect pest damage can reduce the marketability of tomato crops, leading to lower demand from consumers and retailers. Fruits with visible insect damage or deformities may be less desirable to consumers, resulting in lower sales volumes or decreased prices at the market. Pests like the tomato fruit borer may cause internal damage to fruits, making it difficult to detect infestations until after harvest, further impacting consumer confidence in the product [50].

3.4 Loss of export opportunities:

Insect pest damage can affect the export potential of tomato crops, as buyers in international markets may have strict quality standards and reject shipments with visible pest damage. Growers may lose access to lucrative export markets or face penalties for non-compliance with phytosanitary regulations, resulting in lost revenue and market share. Researchers examine the impact of insect damage, fungal infections, and wildlife damage on tomato genotypes grown in a hedgerow system. The research found that variety selection significantly affects fruit production, with 'ACE55′ yielding less healthy unripe fruits. Tomato variety, side, and distance influence insect damage and yield. Protected side experiences more potato beetle damage, while distance affects wild animal damage. Protected side promotes healthy fruit production [51].

4.0 Environmental and Health Costs:

Overreliance on chemical pesticides for pest control can have environmental consequences, such as pollution of soil and water resources, harm to non-target organisms and development of pesticide resistance in pest populations. Health risks to growers, farmworkers, and consumers may also arise from exposure to chemical pesticides or consumption of contaminated produce, leading to additional economic burdens associated with healthcare costs and lost productivity. Pesticides are crucial for agricultural development but can cause severe toxicity to human beings. This review aims to inform policymakers on proper pesticide application methods to minimize exposure and health risks. Four main methods include backpack spraying, hydraulic spraying, aerial spraying, and basal trunk spraying. Humans are exposed to pesticides through various routes, including dermal, oral, and respiratory. Both deterministic and probabilistic human health risk assessments should be used in research. Policymakers should also implement measures like integrated pest management laws and national implementation plans [52].

The economic implications of insect pest damage to tomato crops are multifaceted, encompassing direct losses in yield and revenue, increased production costs, decreased marketability and consumer confidence, loss of export opportunities, and environmental and health costs. Effective pest management strategies that balance economic, environmental, and social considerations are essential for mitigating these impacts and ensuring the sustainability of tomato production systems. Add more references

5.0 Factors influencing the severity of damage by Insect pests in North India

The severity of damage caused by insect pests in tomato crops in North India can be influenced by various factors, including environmental conditions, crop management practices, pest biology, and the presence of natural enemies. A detailed overview of the factors influencing the severity of insect pest damage in tomato crops was presented by Meena and Bairwa [53].

5.1 Environmental Conditions:

Temperature and humidity play a crucial role in the development and activity of insect pests. Warm and humid conditions favour the reproduction and population growth of many pests, including whiteflies, aphids, and thrips. Rainfall patterns can also influence pest abundance, as excessive moisture can create favourable conditions for fungal diseases that may exacerbate pest damage. Climatic variations across different regions of North India can affect the prevalence and severity of insect pests, with certain areas experiencing higher pest pressure due to specific environmental factors. Climate change and extreme weather events significantly impact crop production and agricultural pests. Rising temperatures, atmospheric CO_2 levels, and changing precipitation patterns could expand insect range, increase overwintering survival, and increase the risk of invasive species and plant diseases [54].

5.2 Crop Phenology:

The growth stage of the tomato crop can influence its susceptibility to insect pest damage. Young seedlings and flowering plants are often more vulnerable to certain pests, such as cutworms and aphids, while fruiting plants may be targeted by pests like the tomato fruit borer. Planting date, crop density, and spacing can also affect pest incidence and severity, with dense plantings providing more favourable conditions for pest development and spread. Thrips invade crops through weed control, so weed management strategies for planting susceptible crops like onion, tomato, corn, artichoke, and pumpkin and removing plants with tomato spotted wilt virus symptoms are recommended [55].

5.3 Crop Management Practices:

Crop rotation, intercropping, and polyculture can influence pest populations by disrupting their life cycles and reducing pest pressure. The use of mulches, cover crops, and crop residues can affect microclimate conditions and the presence of natural enemies, which may impact pest populations. Irrigation practices, such as drip irrigation or overhead sprinklers, can influence pest abundance by affecting moisture levels in the field. Farmers must innovate through ecological intensification to combat climate change and boost food production; however, it faces risks like decreased crop yield, management complexity, and increased pest susceptibility. Intercropping, cover cropping, and rotation of legume crops are important strategies to develop agroecosystems through improving bioresource efficiency, soil water holding capacity, and habitat diversity [56]. Studies show benefits for pest control and climate resilience, but few document ecosystem services and labor costs. Strong technical and financial support is needed for farmers to adopt intercropping [57].

5.4 Pest biology and behavior:

The biology and behavior of insect pests, such as their reproductive rate, host preference, and feeding habits, can influence the severity of damage they cause. Pests with rapid reproductive rates, such as aphids and whiteflies, can quickly build up large populations under favourable conditions, leading to more severe damage. Pests with cryptic behavior, such as leafminers and thrips, may be difficult to detect and manage, resulting in unnoticed damage until it becomes severe.The global population growth and technological advancements have significantly impacted agriculture and food production. However, climate change, including increased CO_2 and frequent droughts, poses significant challenges to crop yields and food security [58].

5.5 Natural enemies and biological control:

The presence and activity of natural enemies, including predatory insects, parasitic wasps, and insect-pathogenic fungi, can suppress pest populations and reduce the severity of damage. Factors that influence the abundance and effectiveness of natural enemies, such as habitat diversity, pesticide use, and climatic conditions, can indirectly impact pest damage in tomato crops.

6.0 Management strategies for various insect pests infesting tomato

Managing insect pests in tomato crops requires an integrated approach that combines cultural, biological, mechanical, and chemical control methods. Here's a comprehensive overview of management strategies for various insect pests of tomato crops:

6.1 Cultural Practices: A number of cultural practices are available to manage insect pests in tomatoes, such as [59]. Crop rotation involves rotating tomato crops with non-host crops to disrupt pest life cycles and reduce pest pressure. Sanitation involves removing crop residues and weeds that serve as alternate hosts for pests, thereby reducing pest populations. Plant tomatoes at optimal planting dates and densities minimizes vulnerability to pests. Mulching involves using mulch to conserve moisture, suppress weeds, and create a barrier that impedes pest movement.

6.2 Biological Control: Natural Enemies involve introducing and conserving natural enemies such as predatory insects (e.g., ladybugs, lacewings), parasitic wasps, and insect-pathogenic fungi to suppress pest populations [60]. Biopesticides involve using microbial pesticides and botanical extracts that are toxic to pests but have minimal impact on beneficial organisms. Add more content.

6.3 Mechanical Control: Various mechanical practices involved in managing the insect pests of tomatoes have been presented by Afreen et al. [61]. Handpicking involves physically removing and destroying pests, eggs, and larvae from tomato plants. Traps involve deploying sticky traps or pheromone traps to monitor and capture adult pests, reducing population levels. Barriers involve using physical barriers such as row covers or mesh netting to exclude pests from tomato plants.

6.4 Chemical Control: Insecticides are applied selectively and judiciously, using formulations that are effective against target pests while minimizing harm to non-target organisms. Insecticidal soaps and horticultural oils are used to suffocate and disrupt the cuticle of pests, causing mortality.

6.5 Botanical Biopesticides: Botanical biopesticides are derived from plant extracts and contain compounds that repel, deter, or kill pests. For instance, neem oil, extracted from the neem tree (*Azadirachta indica*), disrupts insect growth and development, inhibits feeding, and acts as a repellent against various pests such as aphids, whiteflies, and spider mites. Botanical extracts, such applied using plant-derived compounds with insecticidal properties, such as neem oil or pyrethrins, to control pests [62, 63]. Biopesticides contain naturally occurring substances that disrupt pest behaviour, physiology, or development. These substances may interfere with pest feeding, mating, or egg-laying processes. For example, insect growth regulators (IGRs) mimic insect hormones, disrupting normal growth and development in pests like caterpillars and beetles.

6.6 Resistant Varieties: Plant tomato varieties that exhibit resistance or tolerance to specific insect pests, reducing the need for chemical controls. Select varieties bred for resistance to key pests such as tomato fruit borer, aphids, or whiteflies, based on local pest pressures and performance data [64].

6.7 Integrated Pest Management (IPM):

Implement a holistic IPM approach that integrates multiple control methods based on pest biology, crop phenology, and environmental conditions. Monitor pest populations regularly using scouting, trapping, or visual inspection techniques to assess pest levels and make informed management decisions. Employ threshold-based management strategies, intervening only when pest populations exceed economically or ecologically acceptable levels [65]. A climate smart pest management practices have been shown in a pyramid [66]. To combat insect pests in tomato crops, a comprehensive approach involving cultural, biological, mechanical, and chemical control methods is crucial for minimizing damage and promoting sustainable practices.

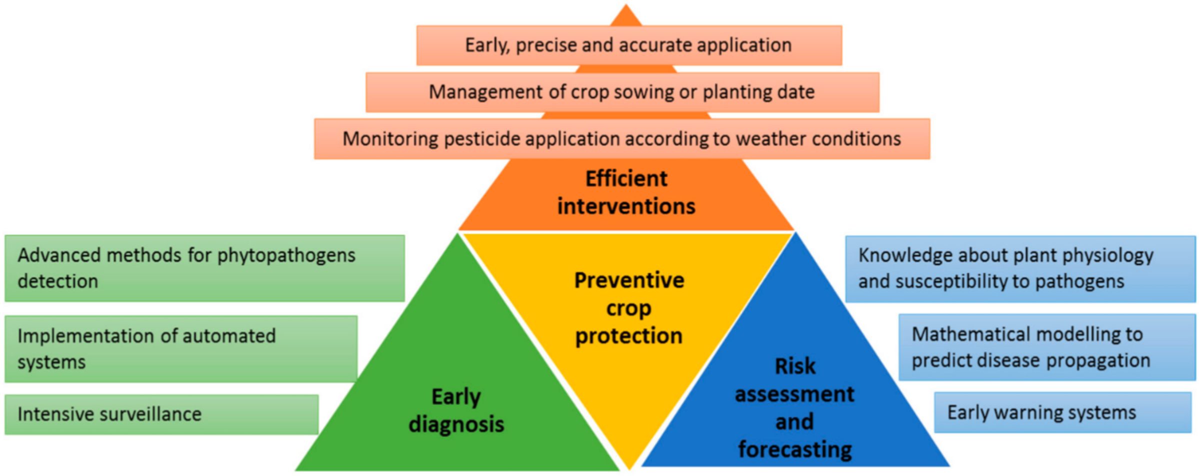

Figure 1. A pyramid showing climate smart pest management for sustainable agriculture (MDPI Source: Bouri et al. [66].

7.0 Principles of IPM and success stories of IPM in North India

Integrated Pest Management (IPM) is a comprehensive pest management strategy that uses various strategies, including cultural, biological, mechanical, and chemical methods, to effectively manage pest populations [67].

7.1 Principles of IPM for Tomato Insect Pests:

Prevention: Emphasize proactive measures to prevent pest outbreaks, such as crop rotation, use of resistant varieties, and sanitation practices to reduce pest habitats. Monitoring: Regularly monitor tomato crops for signs of pest infestations, using methods such as visual inspection, trapping, and sampling to assess pest populations and identify trends over time. Identification: Accurately identify pest species and their life stages to determine appropriate management strategies and assess potential risks to tomato crops. Thresholds: Establish action thresholds based on economic, ecological, or aesthetic considerations to guide decision-making regarding pest control interventions. Only apply control measures when pest populations exceed predetermined thresholds. Integration: Integrate multiple control tactics, including cultural, biological, mechanical, and chemical methods, to create a synergistic approach that maximizes effectiveness while minimizing reliance on any single control measure. Evaluation: Continuously evaluate the effectiveness of IPM strategies through monitoring, record-keeping, and data analysis to make informed adjustments and improvements to pest management plans.

7.2 Case Studies or Success Stories from North India:

Integrated Pest Management (IPM) offers a comprehensive and sustainable approach to managing insect pests in tomato crops [46]. By implementing IPM principles and strategies, growers in North India can effectively mitigate pest damage, reduce environmental impact, and improve the long-term sustainability and profitability of tomato production. Case studies and success stories from the region demonstrate the practical application and benefits of IPM practices in real-world farming contexts.

7.3 Adoption of IPM Practices by Farmers' Cooperatives in Punjab:

7.3.1 Background: Farmers in Punjab faced significant challenges from tomato insect pests, including the tomato fruit borer (*H. armigera*), whitefly (*B. tabaci*), and aphids (*M. persicae),* leading to yield losses and increased pesticide use. Implementation: Several farmers' cooperatives in Punjab collaborated to implement IPM practices for managing tomato insect pests. The cooperatives organized training sessions and workshops to educate farmers about the principles and practices of IPM. They were taught to monitor pest populations, identify natural enemies, and adopt cultural, biological, and mechanical control methods.

7.3.2 Strategies Implemented: Cultural practices involving crop rotation and intercropping with repellent crops were adopted to disrupt pest life cycles. In biological control, farmers introduce natural enemies of pests, such as predatory insects and parasitic wasps, to suppress pest populations. In mechanical control, pheromone traps are deployed to monitor and trap adult whiteflies and fruit borers. In chemical control, farmers minimize pesticide use by applying low-risk formulations and targeted spraying only when pest populations exceed action thresholds.

7.3.3 Outcomes: By implementing IPM practices, farmers in Punjab successfully reduced pest damage, minimized pesticide use, and improved crop yields. The cooperatives reported higher profits, improved environmental sustainability, and enhanced farmer livelihoods. Additionally, the adoption of IPM practices contributed to reduced pesticide residues in tomatoes, ensuring food safety and quality for consumers.

7.4 Success with Resistant Varieties in Haryana:

Tomato growers in Haryana faced challenges from insect pests, such as the tomato fruit borer and aphids, leading to significant yield losses and economic hardship. In response to pest pressure, farmers in Haryana began adopting resistant tomato varieties that were bred for tolerance or resistance to specific insect pests. These varieties exhibited traits such as thicker fruit skins, reduced susceptibility to pest damage, and enhanced tolerance to environmental stresses [68].

7.4.1 Strategies Implemented: To use resistant varieties, farmers planted resistant tomato varieties that were less susceptible to insect pests, such as the tomato fruit borer and aphids. To adopt IPM practices, farmers implemented techniques such as crop rotation, monitoring, and judicious pesticide use to manage pest species and prevent resistance development. The adoption of resistant tomato varieties has proved highly successful in Haryana, with farmers reporting reduced pest damage, improved crop yields, and increased profits. By relying less on chemical pesticides, growers were able to reduce production costs, minimize environmental impact, and ensure a more sustainable approach to tomato production [69].

7.5 Implementation of IPM Practices in Farmer Cooperatives in Western Uttar Pradesh:

7.5.1 Background: Tomato growers in Western Uttar Pradesh faced challenges from insect pests such as the tomato fruit borer (*H. armigera*), whitefly *(B. tabaci*), and aphids (*M. persicae*), resulting in yield losses and increased pesticide usage [70].

7.5.2 Implementation: Several farmer cooperatives in Western Uttar Pradesh collaborated with agricultural extension services to implement IPM practices for managing tomato insect pests. Extension officers provided training sessions and demonstrations on IPM principles and practices, focusing on cultural, biological, and mechanical control methods.

7.5.3 Strategies Implemented:

As part of their cultural practices, farmers have adopted crop rotation and intercropping with pest-repellent crops to disrupt the life cycles of pests. Under biological control, natural enemies such as predatory insects and parasitic wasps are introduced and conserved to suppress pest populations. For mechanical control, pheromone traps were deployed to monitor and trap adult pests, thereby reducing population levels. For chemical control, farmers minimize pesticide use by applying selective and low-toxicity formulations only when pest populations exceed action thresholds.

7.5.4 Outcomes: Through the adoption of IPM practices, farmers in Western Uttar Pradesh successfully reduced pest damage, minimized pesticide usage, and improved crop yields. The cooperatives reported higher profits, enhanced environmental sustainability, and improved farmer livelihoods. Additionally, the implementation of IPM practices contributed to reduced pesticide residues in tomatoes, ensuring food safety and quality for consumers.

7.6 Success with Resistant Varieties and Biological Control in Eastern Uttar Pradesh:

Tomato growers in eastern Uttar Pradesh face challenges from insect pests, such as the tomato fruit borer and aphids, which lead to significant yield losses and economic hardships. In response to pest pressure, farmers in eastern Uttar Pradesh began adopting resistant tomato varieties that were bred for tolerance or resistance to specific insect pests. Additionally, farmers implemented biological control measures to manage pest populations.

7.6.1 Strategies Implemented:

Farmers planted tomato varieties that were resistant to pests and exhibited traits such as thicker fruit skins, reducing susceptibility to pest damage. To achieve biological control, natural enemies such as predatory insects and parasitic wasps are conserved and augmented to suppress pest populations in tomato crops. As an outcome, the adoption of resistant tomato varieties coupled with biological control measures proved highly successful in Eastern Uttar Pradesh. Farmers reported reduced pest damage, improved crop yields, and increased profits. By relying less on chemical pesticides, growers can reduce production costs, minimize environmental impact, and ensure a more sustainable approach to tomato production [68].

These case studies from North India demonstrate the effectiveness of integrated pest management (IPM) approaches in managing tomato insect pests. By combining cultural, biological, mechanical, and chemical control methods, farmers have successfully minimized pest damage, reduced pesticide use, and improved crop yields and profitability, contributing to the sustainability and resilience of tomato production in the region.

7.7 Successes and challenges in adoption of IPM by tomato growers in North India:

The adoption of Integrated Pest Management (IPM) practices in tomato crops in North India has shown both successes and challenges. Here's an overview of the achievements and obstacles faced in the adoption of IPM in tomato cultivation:

One of the significant achievements of IPM adoption in tomato crops in North India is the reduction in pesticide usage [71]. By implementing IPM practices such as crop rotation, biological control, and cultural practices, farmers have been able to minimize reliance on chemical pesticides [72]. This has led to decreased environmental pollution, improved farmworker safety, and reduced health risks for consumers. The adoption of IPM practices has resulted in more effective pest management in tomato crops. Farmers have reported reduced pest damage and improved crop yields through the integration of various control methods. Biological control measures, such as the conservation of natural enemies and the use of resistant varieties, have played a crucial role in suppressing pest populations and maintaining crop health. IPM adoption has contributed to the sustainability of tomato production systems in North India. By promoting practices that conserve natural resources, minimize environmental impact, and support ecosystem services, IPM has helped create more resilient and ecologically balanced agricultural systems. Farmers practising IPM have reported improved soil health, water conservation, and biodiversity on their farms. The adoption of IPM practices has brought economic benefits to tomato growers in North India. By reducing production costs associated with pesticide purchase and application, farmers practising IPM have achieved higher profits and improved financial stability. Additionally, IPM adoption has opened up new market opportunities for sustainably grown tomatoes, attracting premium prices from environmentally conscious consumers.

8.0 Challenges:

A significant challenge in the adoption of IPM in tomato crops is the lack of knowledge and awareness among farmers. Many growers in North India are unaware of IPM principles and practices or lack access to training and extension services. Addressing this knowledge gap and providing farmers with technical assistance and capacity-building programs is essential for promoting widespread adoption of IPM. Limited access to resources, including information, technology, and financial support, poses a barrier to the adoption of IPM in tomato cultivation. Smallholder farmers, in particular, may face challenges in accessing inputs such as biological control agents, resistant varieties, and monitoring tools. Increasing accessibility to resources through government programs, research initiatives, and public-private partnerships can help overcome this challenge. The lack of market demand and incentives for sustainably grown tomatoes can hinder the adoption of IPM practices. Without adequate market premiums or certification schemes for IPM-produced tomatoes, farmers may be less motivated to invest in IPM adoption. Creating market incentives and certification programs that recognize and reward environmentally friendly farming practices can encourage more growers to adopt IPM. Pest resistance to control measures and the impacts of climate change pose significant challenges to IPM adoption in tomato crops. Pests such as the tomato fruit borer and whitefly may develop resistance to pesticides or overcome biological control agents, making management more challenging. Additionally, changing climatic conditions, such as temperature fluctuations and erratic rainfall patterns, may alter pest dynamics and require adaptation of IPM strategies. Implications of modified IPM practices in the view of climate change is necessary to enhance the food security (Figure 2).

While the adoption of IPM practices in tomato crops in North India has demonstrated successes in reducing pesticide use, improving pest management, enhancing sustainability, and generating economic benefits, several challenges remain. Addressing knowledge gaps, improving access to resources, creating market incentives, and addressing pest resistance and climate change is critical for promoting the widespread adoption of IPM and ensuring the long-term sustainability of tomato production in the region.

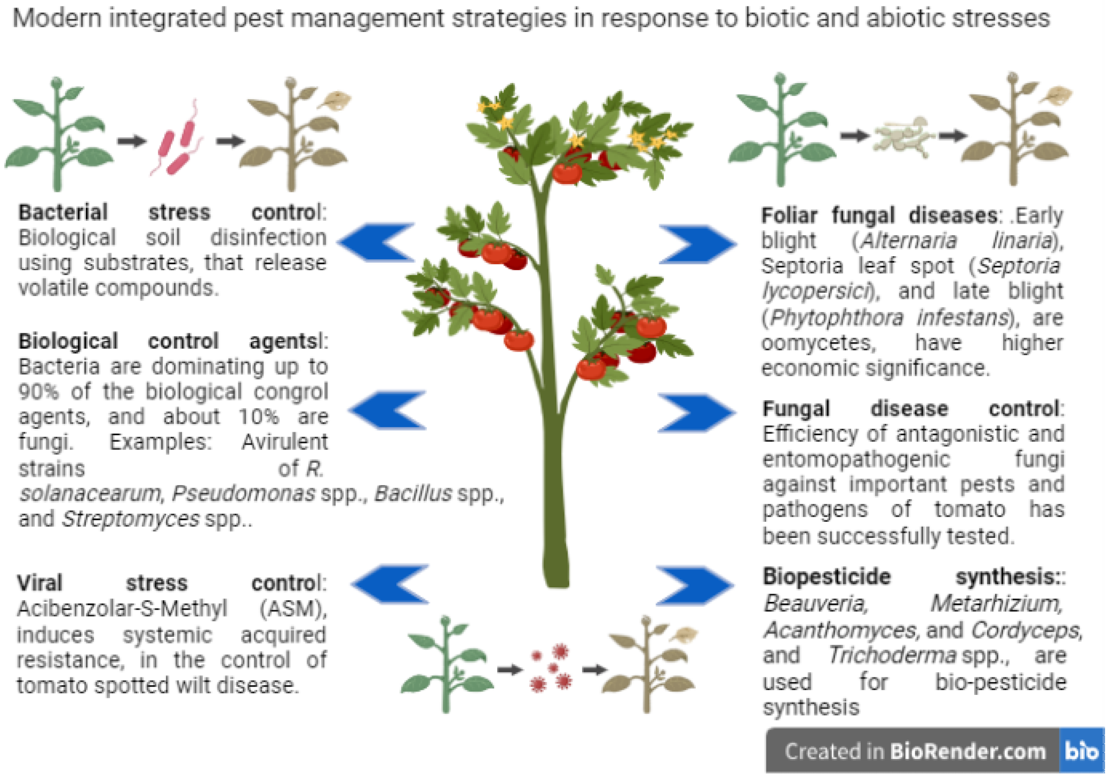

Figure 2. Pest management strategies for mitigating biotic and abiotic stress under changing climatic scenarios

8.1 Research gaps and areas for further investigation

Research on Integrated Pest Management (IPM) adopted by farmers for tomato insect pests in North India has made significant strides, but several research gaps and areas for further investigation remain. Addressing these gaps is essential for enhancing the effectiveness and sustainability of IPM practices in tomato cultivation. Here are some research areas that warrant attention. Evaluate the long-term efficacy and sustainability of IPM practices adopted by farmers for managing tomato insect pests. Longitudinal studies can provide insights into the durability of IPM interventions and their impact on pest populations, crop yields, and environmental health. Investigate the influence of climate change on the dynamics of tomato insect pests and the effectiveness of IPM strategies. Assess how changing temperatures, rainfall patterns, and extreme weather events affect pest phenology, population dynamics, and crop susceptibility to pests. Study the development and management of insecticide resistance in tomato insect pests. Assess the prevalence of resistance mechanisms in pest populations and evaluate resistance management strategies, including rotation of insecticides, use of alternative control methods, and development of novel pest management technologies. Explore the potential of indigenous and exotic natural enemies for biological control of tomato insect pests. Investigate the efficacy, compatibility, and persistence of predatory insects, parasitic wasps, and entomopathogenic fungi under diverse agroecological conditions in North India. Evaluate the genetic diversity of tomato germplasm for resistance or tolerance to key insect pests. Identify novel sources of resistance in wild and cultivated tomato species and develop breeding strategies to incorporate resistance traits into commercial tomato varieties adapted to North Indian agroclimatic conditions. Examine the socioeconomic drivers and barriers influencing farmer adoption of IPM practices for tomato insect pests. Investigate factors such as access to information, extension services, market incentives, credit, and social networks that influence farmer decision-making and uptake of IPM technologies. Assess the effectiveness of extension and education programs in promoting IPM adoption among tomato growers in North India. Evaluate the impact of farmer training workshops, demonstration plots, participatory research, and farmer field schools on knowledge, attitudes, and practices related to IPM. Conduct cost-benefit analyses of IPM adoption for tomato insect pests in North India. Estimate the economic returns, profitability, and financial risks associated with implementing IPM practices compared to conventional pest management approaches. Evaluate the socio-economic implications for different categories of farmers, including smallholders, medium-scale, and large-scale growers.

By addressing these research gaps and areas for further investigation, scientists, policymakers, and extension specialists can advance the development and adoption of sustainable IPM strategies for managing tomato insect pests in North India. Collaborative research efforts that integrate multidisciplinary approaches and engage stakeholders across the agricultural value chain will be essential for achieving meaningful progress in this field. Add more references with similar studies.

9.0 Conclusion

In conclusion, research on Integrated Pest Management (IPM) adopted by farmers for tomato insect pests in North India has made significant strides, but several critical gaps and areas for further investigation have been identified. Addressing these gaps is crucial for enhancing the effectiveness, sustainability, and adoption of IPM practices in tomato cultivation. Key research areas include evaluating the long-term efficacy of IPM strategies, assessing the impact of climate change on pest dynamics, managing insecticide resistance, exploring biological control agents and host plant resistance, understanding socioeconomic factors influencing farmer adoption, and conducting economic analyses of IPM adoption. By addressing these research needs through collaborative efforts involving scientists, policymakers, extension specialists, and farmers, we can advance the development and adoption of sustainable IPM strategies tailored to the unique agroecological conditions of North India. Ultimately, this research will contribute to improving pest management practices, reducing pesticide use, enhancing crop yields, and promoting the long-term sustainability of tomato production in the region.

Climate change and extreme weather events are causing significant impacts on crop production and agricultural pests. Rising temperatures, CO_2 levels, and changing precipitation patterns can expand insect range, increase overwintering survival, and increase the risk of invasive species and diseases. This review also discusses the underserved small-scale farm sector and emphasizes the importance of IPM practices in enhancing local food security. It highlights challenges and opportunities in implementing IPM in small-scale production, including adapting to different scales, identifying potential approaches not widely used, and addressing knowledge gaps. At economic injury level, pesticides are suggested through four main methods including backpack spraying, hydraulic spraying, aerial spraying, and basal trunk spraying. Integrated approaches are recommended for effective management, and strategies such as intercropping, cover cropping, and rotation of legume crops are essential for developing agroecosystems and minimizing damage.

10. Ethical statement:

Ethical issues do not apply to this review article. The paper does not involve a study on animals.

11. Conflict of interest:

The authors declare that there is no conflict of interest among authors for the publication of this manuscript in this journal.

12. Declaration Statement:

The authors declare that they have not received any financial assistance, and they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

13. References

1. M. Safna, K.V. Naik, V.S. Desai, M. S. Karmarkar, B.D. Shinde, and P. P. Raut. Evaluation of the efficacy of some insecticides against fruit borer, Helicoverpa armigera (Hubner) infesting tomato. Int. J. Chem. Stud, ***6*(2)**, 1158-1163 (2018).

2. D.L. Madhavi, and D.K. Salunkhe. Tomato. In Handbook of Vegetable Science and Technology (pp. 189-220). CRC Press (1998).

3. A.Raiola, M.M. Rigano, R. Calafiore, L. Frusciante, and A. Barone. Enhancing the health-promoting effects of tomato fruit for biofortified food. Mediators of Inflammation (2014).

4. S.S. Abbas, M.F. Shahzad, J. Iqbal, A. Ullah, A. Batool, M. Nadeem, ... and M.K. Hafeez-ur-Rehman. *Trichogramma chilonis* as parasitoid: An eco-friendly approach against tomato fruit borer, *Helicoverpa armigera*. J. Agric. Sci, **12**(2), 167 (2020).

5. G.P. Fitt, and S.C. Cotter. The Helicoverpa problem in Australia: biology and management. Heliothis/Helicoverpa Management, CRC Press, pp 57-74 (2005).

6. K.P. Herald, and A.R. Tayde. Biology and morphology of tomato fruit borer, *Helicoverpa armigera* (Hubner) under Allahabad conditions. J. Entom. Zool. Studies **6**(4), 1734-1737 (2018).

7. R.N.C. Guedes, and H.A.A. Siqueira. The tomato borer Tuta absoluta: insecticide resistance and control failure. *CABI Reviews*, 1-7 (2012).

8. T.I. Ofuya, A.I. Okunlola, and G.N. Mbata. A review of insect pest management in vegetable crop production in Nigeria. *Insects*, **14**(2), 111 (2023).

9. S. Singh, S. Watts, I. Kaur, I. Rodriguez, J. Ayala, D. Rodriguez, ... and R. Kariyat. Sex and stress modulate pupal defense response in tobacco hornworm. Curr. Zool. **69**(5), 592-599 (2023).

10. N. Volesky, and M. Murray. High Tunnel Pest Management-Caterpillars. All Current Publications (2021).

11. D. Sharma, A. Maqbool, V.V.S. Jamwal, K. Srivastava, and A. Sharma. Seasonal dynamics and management of whitefly (*Bemesia tabaci* Genn.) in tomato (*Solanum esculentum* Mill.). Braz. Arch. Biol. Technol. **60** (2017).

12. I.M. Fortes, R. Fernández-Muñoz, and E. Moriones. Host plant resistance to Bemisia tabaci to control damage caused in tomato plants by the emerging crinivirus tomato chlorosis virus. Front. Plant Sci. **11,** 585510 (2020).

13. Food and Agriculture Organization of the United Nations, The state of food insecurity in the World: The multiple dimensions of food security. Food and Agriculture Organization, Rome, Italy, (2013).

14. International Food Policy Research Institute, Global food policy report: 2016, International Food Policy Research Institute, Washington, D.C., (2016).

15. E. Stokstad. Devastating banana disease may have reached Latin America, could drive up global prices. Science **365**, 207–208 (2019).

16, P.M.A. Bourke. Emergence of potato blight, 1943-46. Nature **203,** 805–808 (1964).

17. S.Y. Padmanabhan. The Great Bengal famine. Annu. Rev. Phytopathol. **11**, 11–24 (1973).

18. J. Avelino, M. , S. Georgiou et al. The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. Food Sec. 7, 303–321 (2015). https://doi.org/10.1007/s12571-015-0446-9

19. T.M. Perring, D. Battaglia, L.L. Walling, I. Toma, and P. Fanti. Aphids: biology, ecology, and management. In Sustainable Management of Arthropod Pests of Tomato (pp. 15-48). Academic Press (2018).

20. W. Wakil, G.E. Brust, and T. Perring (Eds.). Sustainable Management of Arthropod Pests of Tomato. Academic Press (2017).

21. F. Hemmati, S.A.A. Behjatnia, A. Moghadam, and A. Afsharifar. Induction of systemic resistance against cucumber mosaic virus (CMV) and tomato yellow leaf curl virus (TYLCV) in tomato. *International Journal of Pest Management*, 1-14 (2023).

22. S.I.T.I. Herlinda. Ecology of Liriomyza spp. (Diptera: Agromyzidae) in field vegetables in South Sumatera. In *Proceedings of an International Seminar on Organic Farming and Sustainable Agriculture in the Tropics and Subtropics* (pp. 8-9) (2003).

23. L. Gianessi. The Benefits of insecticide use: Tomatoes. Crop Life Foundation, Washington, USA, **18** (2009).

24. O. Demirozer, K. Tyler-Julian, J. Funderburk, N. Leppla, and S. Reitz. Frankliniella occidentalis (Pergande) integrated pest management programs for fruiting vegetables in Florida. Pest Management Science, **68**(12), 1537-1545 (2012).

25. E.D. Meck, G.G. Kennedy, and J.F. Walgenbach. Effect of *Tetranychus urticae* (Acari: Tetranychidae) on yield, quality, and economics of tomato production. Crop Protection, **52,** 84-90 (2013).

26. C.R. Cardoso. Agressividade de *Alternaria tomatophila*, *A. grandis* e *A. solani* em Batateira e Tomateiro. Ph.D. Thesis, Universidade Federal de Viçosa: Viçosa, Brazil (2010).

27. F.J. Ferrandino, and W.H. Elmer. Reduction in tomato yield due to Septoria leaf spot. *Plant Dis. 76*, 208–211 (1992).

28. Utkhede, R.S., and Mathur, S. 2006. Preventive and curative biological treatments for control of *Botrytis cinerea* stem canker of greenhouse tomatoes. *BioControl 51*, 363–373.

29. T. Momol, P. Ji, K. Pernezny, R. McGovern, and S. Olson. Three Soilborne Tomato Diseases Caused by *Ralstonia* and *Fusarium* Species and their Field Diagnostics. EDIS **205**, 1–6 (2008).

30. A. Rotter, P. Nikolić, N. Turnšek, P. Kogovšek, A. Blejec, K. Gruden and M. Dermastia. Statistical modeling of long-term grapevine response to '*Candidatus* Phytoplasma solani' infection in the field. Eur J. Plant Pathol. **150**, 653–668 (2018).

31. G. Sharabani, S. Manulis-Sasson, L. Chalupowicz, M. Borenstein, R. Shulhani, M. Lofthouse, M. Sofer, O. Frenkel, O. Dror, and D. Shtienberg. Temperature at the early stages of *Clavibacter michiganensis* subsp. *michiganensis* infection affects bacterial canker development and virulence gene expression. Plant Pathol. **63**, 1119–1129 (2014).

32. F. Quaglino, Y. Zhao, P. Casati, D. Bulgari, P.A. Bianco, W. Wei, and R.E. Davis. "*Candidatus* Phytoplasma solani", a novel taxon associated with stolbur and bois noir related diseases of plants. Int. J. Syst. Evol. Microbiol. **63**, 2879–2894 (2013).

33. M.A. Sevik, and M. Arli-Sokmen. Estimation of the effect of *Tomato spotted wilt virus* (TSWV) infection on some yield components of tomato. Phytoparasitica **40**, 87–93 (2012).

34. K.P.A. Mahjabeen, N. Sarwar, M.Y. Saleem, M. Asghar, Q. Iqbal, and F.F. Jamil. Effect of cucumber mosaic virus infection on morphology, yield and phenolic contents of tomato. Arch. Phytopathol. Pflanzenschutz **45**, 766–782 (2012).

35. M. Lapidot, M. Friedmann, O. Lachman, Y. Antignus, S. Nahon, S. Cohen, and M. Pilowsky. Comparison of resistance level to tomato yellow leaf curl virus among commercial cultivars and breeding lines. Plant Dis. **81**, 1425–1428 (1887).

36. E. Noris, and L.Miozzi. Real-Time PCR Protocols for the Quantification of the Begomovirus Tomato Yellow Leaf Curl Sardinia Virus in Tomato Plants and in Its Insect Vector. Methods Mol. Biol. **1236,** 61–72 (2015).

37. Z.Y. Yan, H.Y. Ma, S.L. Han, C. Geng, Y.P. Tian, X.D. Li. First report of Tomato brown rugose fruit virus infecting tomato in China. Plant Dis. **103**, 2973 (2019).

38. M. Imran, M.A. Khan, M. Fiaz, M. Azeem, and M. Mustafa. Influence of environmental conditions on tomato mosaic virus disease development under natural condition. Pak. J. Phytopathol. **25**, 117–122 (2013).

39. G. Parrella. Sources of resistance in wild *Solanum* germplasm (section *Lycopersicon*) to parietaria mottle virus, an emerging virus in the Mediterranean basin. Plant Pathol. **69,** 1018–1025 (2020).

40. J. Peters, R. Mumford, R. van der Vlugt, A. Alfaro Fernandez, G. Bese, J. Glyn, C. Lambourne, and M. Schenk. The Effect of *Pepino mosaic virus* on tomato yield. Acta Hortic. **914**, 203–206 (2011).

41. A.E. Mackie, M.J. Barbetti, B. Rodoni, S.J. McKirdy, and R.A.C. Jones. Effects of a Potato Spindle Tuber Viroid Tomato Strain on the Symptoms, Biomass, and Yields of Classical Indicator and Currently Grown Potato and Tomato Cultivars. Plant Dis. **103**, 3009–3017 (2019).

42. N. Gupta, S.C. Verma, P. L. Sharma, M. Thakur, P. Sharma, and D. Devi. Status of invasive insect pests of India and their natural enemies. J. Entom. Zool. Studies **7**(1), 482-489 (2019).

43. D.R. Kachave, M.M. Sonkamble, and S.K. Patil. Population dynamics of major insect pests infesting to tomato, *Lycopersicon esculentum* (Miller). J. Pharmacog. Phytochem. **9**(3), 344-348 (2020).

44. M.A. Hamza, M. Ishtiaq, M.A. Mehmood, M.A. Majid, M. Gohar, E. Radicetti, R. Mancinelli, N. Iqbal, and S. Civolani. Management of Vegetable Leaf Miner, Liriomyza Spp., (Diptera: Agromyzidae) in Vegetable Crops. Horticulturae **9**, 255 (2023). https://doi.org/10.3390/horticulturae9020255

45. D. Kumar, P. Kumari, R. Kamboj et al. Entomopathogenic nematodes as potential and effective biocontrol agents against cutworms, Agrotis spp.: present and future scenario. Egypt J Biol Pest Control **32**, 42 (2022) https://doi.org/10.1186/s41938-022-00543-5

46. C. Bragard, K. Dehnen-Schmutz, F. Di Serio, P. Gonthier, M.A. Jacques, J.A. Jaques Miret et al. Pest categorisation of *Thrips palmi*. EFSA J. 17(2):e05620 (2019) doi: 10.2903/j.efsa.2019.5620.

47. W.H. Lange, and L. Bronson. Insect pests of tomatoes. Annu. Rev. Entomol. **26**(1), 345-371 (1981).

48. S.E. Mrosso, P.A. Ndakidemi, and E.R. Mbega. Farmers' Knowledge on Whitefly Populousness among Tomato Insect Pests and Their Management Options in Tomato in Tanzania. Horticulturae **9**, 253 (2023). https://doi.org/10.3390/horticulturae9020253

49. T.R. Grasswitz. Integrated Pest Management (IPM) for Small-Scale Farms in Developed Economies: Challenges and Opportunities. Insects. **10**(6):179. (2019) doi: 10.3390/insects10060179.

50. R.C. Stephenson, C.E. Coker, B.C. Posadas, G.R. Bachman, R.L. Harkess, J. J. Adamczyk, and P.R. Knight. Economic effect of insect pest management strategies on small-scale tomato production in Mississippi. HortTechnology, **30**(1), 64-75 (2020).

51. M. Mustafa, J.A. Adjei, L. Menyhárt, L. Csambalik, and Z. Szalai. Pest and Disease Impact on Tomato Genotypes in a Hedgerow System. Biol. Life Sci. Forum **27**, 47. (2023) https://doi.org/10.3390/IECAG2023-15819

52. M. Tudi, H. Li, H. Li, L. Wang, J. Lyu, L. Yang, S. Tong, Q.J. Yu, H.D. Ruan, A. Atabila, D.T. Phung, R. Sadler, and D. Connell. Exposure Routes and Health Risks Associated with Pesticide Application. Toxics. **10**(6):335 (2022). doi: 10.3390/toxics10060335.

53. LK. Meena, and B. Bairwa. Influence of abiotic and biotic factors on the incidence of major insect pests of tomato. The Ecoscan, **8**(3-4), 309-313 (2014).

54. S. Skendžić, M. Zovko, I.P. Živković, V. Lešić, and D. Lemić. The Impact of Climate Change on Agricultural Insect Pests. Insects. **12**(5):440 (2021). doi: 10.3390/insects12050440.

55. J. Kroschel, N. Mujica, J. Okonya, and A. Alyokhin. Insect Pests Affecting Potatoes in Tropical, Subtropical, and Temperate Regions. In: Campos, H., Ortiz, O. (eds) The Potato Crop. Springer, Cham. (2020) https://doi.org/10.1007/978-3-030-28683-5_8

56. C. Kumar, A.K. Singh, D.R. Joshi, and D.E. Clay. The Ecology of Intercropping Systems, Tree-Cover Dynamics of Grazing Lands, and Cover Crops for Soil Management. In: Agroecological Approaches for Sustainable Soil Management (Prasad MNV and Kumar C, Editors). Publisher: Johns Willey and Sons Lts., UK, pp 357-372 (2023); https://doi.org/10.1002/9781119911999.ch16

57. C.P. Huss, K.D. Holmes, and C.K. Blubaugh. Benefits and Risks of Intercropping for Crop Resilience and Pest Management. J. Econ. Entom. 115(5): 1350–1362 (2022), https://doi.org/10.1093/jee/toac045

58. B. Subedi, A. Poudel, and S. Aryal. The impact of climate change on insect pest biology and ecology: Implications for pest management strategies, crop production, and food security. J. Agric. Food Res. **14**, 100733 (2023).

59. P.H.B. Togni, W.A. Marouelli, A.K. Inoue-Nagata, C.S.S. Pires, and E.R. Sujii. Integrated cultural practices for whitefly management in organic tomato. J Appl. Entomol. **142**(10), 998-1007 (2018).

60. S. Lahiri, and D. Orr. Biological control in tomato production systems: Theory and practice. In Sustainable Management of Arthropod Pests of Tomato, pp. 253-267 (2018). Academic Press.

61. S. Afreen, M. Rahman, M.M.U.I. Islam, M. Hasan, and S. Islam. Management of insect pests in tomato (*Solanum lycopersicon* L.) under different planting dates and mechanical support. J. Sci. Technol. Environ. Inform. **5**(1), 336-346 (2017).

62. E.N. Yardim, and C.A. Edwards). The influence of chemical management of pests, diseases and weeds on pest and predatory arthropods associated with tomatoes. Agric. Ecosys. Environ. **70**(1), 31-48 (1998).

63. W. Akhter, F.M. Shah, M. Yang, S. Freed, M. Razaq, A.G. Mkindi, and M. Hanif. Botanical biopesticides have an influence on tomato quality through pest control and are cost-effective for farmers in developing countries. Plos One, **18**(11), e0294775 (2023).

64. L. Depenbusch, T. Sequeros, P. Schreinemachers, M. Sharif, K. Mannamparambath, N. Uddin, and P. Hanson. Tomato pests and diseases in Bangladesh and India: farmers' management and potential economic gains from insect resistant varieties and integrated pest management. Int. J. Pest Manag. 1-15 (2023).

65. M.C. Picanço, L. Bacci, A.L.B. Crespo, M.M.M. Miranda, and J.C. Martins. Effect of integrated pest management practices on tomato production and conservation of natural enemies. Agr. Forest Entomol. **9**(4), 327-335 (2007).

66. M. Bouri, K.S. Arslan, and F. Sahin. Climate-Smart Pest Management in Sustainable Agriculture: Promises and Challenges. Sustainability **15**, 4592 (2023). https://doi.org/10.3390/su15054592

67. M. Barzman, P. Bàrberi, A.N.E. Birch, P. Boonekamp, S. Dachbrodt-Saaydeh, B. Graf, ... and M. Sattin. Eight principles of integrated pest management. Agron. Sustain. Dev. **35**, 1199-1215 (2015).

68. M. Singh, N. Pandey, and O.P. Sharma. IPM concept and strategies for sustainable agriculture. In Integrated Pest Management in Diverse Cropping Systems (pp. 31-59). Apple Academic Press (2023).

69. O.P. Lal, and S.K. Lal. Failure of control measures against *Heliothis armigera* (Hübner) infesting tomato in heavy pesticidal application areas in Delhi and satellite towns in western Uttar Pradesh and Haryana (India). J. Entomol. Res. **20**(4), 355-364 (1996).

70. A. Kumar, G. Tiwari, and A.K. Singh. IPM practices for insect pests of major vegetable crops: An overview. Pharma. Innov. J. **11**(3), 1728-1734 (2022).

71. M.S. Sharifzadeh, G. Abdollahzadeh, and C.A. Damalas. Farmers' behaviour in the use of integrated pest management (IPM) practices: perspectives through the social practice theory. International Journal of Pest Management, 1-14 (2023).

72. P. Han, C. Rodriguez-Saona, M.P. Zalucki, S.S. Liu, and N. Desneux. A theoretical framework to improve the adoption of green Integrated Pest Management tactics. Commun. Biol. **7**(1), 337 (2024).