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Sustainable Pest Management using Modern Tools and Techniques

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Abstract

Climate resilient agriculture aims to mitigate the adverse effects of climate change on agricultural productivity by managing farmlands, crops, livestock and forests. In India, pests and diseases result in a significant yield loss, with insect pests alone causing 18-20% damage to crop production. Factors contributing to this loss include the emergence of secondary pests as primary pests, climate change, resistance breakdowns, new biotypes, invasive pests and human activities. To address these challenges, a sustainable insect pest management strategy integrating traditional Integrated Pest Management (IPM) principles with modern technologies such as use of drone for surveillance of insect pest and application of plant protection chemicals, using of OMICs approach for early pest detection and use of genetic techniques like RNAi or RIDL and CRISPR CAS9 for pest control. This chapter discusses the need to revamp existing IPM strategies to incorporate artificial intelligence for pest identification and monitoring, nanotechnology for efficient pest trapping and the development of organic nano-pesticides. Emphasis is placed on ecologically sound, environmentally safe and sustainable pest management practices that align with modern scientific advancements. The integration of these modern approaches and technologies into pest management can fill the gaps left by IPM, promoting a more sustainable and environmentally friendly future for agriculture. The future of pest management involves a holistic approach, leveraging biotechnological tools, IoT, AI-based forecasting and robust extension services to ensure sustainability and self-sufficiency in Indian agriculture.

Keywords Biotechnological tools, IoT, Modern tools, Sustainable pest management

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1. Introduction

Climate resilient agriculture is a comprehensive strategy for managing the farmlands, crops livestock and forest that counteracts the negative impact of climate change on agricultural productivity. In India the pest and diseases alone cause a yield loss to the tune of 30-35% (Rathee and Dalal, 2018). The insect pest alone causes severe damage to the crop produce 18-20% damage (Sharma *et al.*, 2017). The key factors that are responsible for this heavy loss due to insect pest are shifting of secondary pest to primary pest or key pest status, climate change, breakdown of resistance or evolution of new biotype, invasive insect pest, anthropogenic activities *etc.* In order to contain the insect pest damage and its loss a sustainable insect pest management strategy encompassing the basic principle of Integrated pest management, also accommodating the advancements of modern protection technologies like utilizing drone cameras for insect pest monitoring, drone application of plant protection chemicals, utilization of OMICs approach to diagnose the invasive pest at early stage and use of RNAi or RIDL or CRISPR-CAS9 to contain its spread and survival *etc.* has to be formulated. In short, the current chapter discusses about the appropriate utilization of latest technologies for managing the emerging pest problems in a sustainable way. The current time needs to revamp the existing IPM strategies to so as to realign according to latest developments of science like artificial intelligence for diagnosing the new insect or biotype or resistance pest population, modern ways of pest monitoring, scouting and surveillance. The advancements in nanotechnology had revolutionized the semio-chemical sciences wherein the nano-pheromones and nano-dispensers help in efficient monitoring and trapping of insect pest and also it meets the climate resilience. This chapter orients the modern advancements with conventional IPM for sustainable pest management so as to attain self-sufficiency along with nutritional sufficiency in India.

2. Existing Pest Management Strategy

The ideology about integrated pest management is being practiced for long time, which is a multifaceted approach focused primarily on ecological and economical slant of pest management. Numerous reports stated that a wide range of factors, such as level of schooling, social and economic conditions, concern for the environment, rational thought, ethical beliefs, regulatory aspects, government policies, accessibility to IPM tools, extension training, consumer preference and retail marketing, influence the implementation of integrated pest management (Jayasooriya and Aheeyar, 2016; Rezaei *et al.*, 2019). It has been observed from the survey that within the farming communities in India, 93% of farmers had adopted chemical control; 51% of farmers get recommendations from dealers, 22% from agricultural officials and almost 73% of farmers initiate plant protection measures when they notice pest first time itself, regardless of the pest density, crop stage or relationship to damage. This shows that though many researches and policies have been developed, the seepage of this management strategy is very less. Table 1 shows the existing IPM practices as suggested by Directorate of Plant Protection and Quarantine.

Table 1: Existing different pest control strategies

Cultural method	The spatial and temporal modifications in the usual agronomic practices such that the environment will not favor the survivability and lifecycle of insects. For example: Irrigation management, nutrient management.
Physical and mechanical practices	Utilizing temperature, moisture and radiant energies with the intention to reduce the pest density is included in physical control measures. Use of manual forces or mechanical tool such as iron hooks, sieving and winnowing comes under mechanical control practices.
Host plant resistance	Use of resistant varieties. The mechanism of resistance could be because of antixenosis, antibiosis or tolerance.
Semiochemicals	Utilizing/ mimicking the natural chemicals produced by the insects for their communication.
Biological control • Macrobial • Microbial (Biopesticides)	Use of predators and parasitoids against the pests is called as macrobial control. Exploiting the microorganisms that has the ability to cause disease in insects such as bacteria, virus, fungi, Entomo-pathogenic nematodes etc. is called microbial control. The formulations of these microbial control agents are called as biopesticides.

3. Need of Sustainable Pest Management

Integrated Pest Management was the concept developed for ensuring food security but still there are certain bickering that sustainable pest control strategies should also be included to ensure environment's as well as being's health security. Even with the best of intentions, harsh truths must be acknowledged. Researchers have noted that the following significant flaws: i) IPM principles, practices and policies that are inconsistent; ii) Farmers are rarely involved in the development of IPM technology and frequently lack a fundamental knowledge of the ecological concepts that underpin it; iii) Integration of practices has proceeded down coincidental paths, proven unsuccessful and produced unacceptable results by deviating from the core IPM principles; iv) Foundation of plant health programs is still, chemical control in many regions; v) In addition, IPM research frequently lags behind, frequently makes mistakes and gives less consideration to ecology and the ecological structure of farming systems (Deguine *et al.*, 2021). Once these pesticides reach the ecosystem, they have a range of consequences on animal kingdom and general flora (Tudi *et al.*, 2021).

Similar to IPM, Sustainable Pest Management (SPM) incorporates a variety of methods and technologies and directs pest control decisions. In addition, SPM also considers:

- Effects on equity and social groups
- Links to more general environmental concerns such the preservation of water, the natural world, soil health and the impact of climate variability
- A more thorough analysis of the advantages and disadvantages of the economy

So, there is an urgent need to formulate pest management strategies in a sustainable way. And at the same time, the technological improvements and techniques developed have lot more to do with the sustainable pest management by covering up the gaps of IPM.

4. Pest Management through Optimization

The integrated pest management propounds to use optimum inputs like seed rate, sowing time, fertilizer and irrigation. Some of the pest problems are more in crowded plant stand rather than sparse whereas few diseases or insect pest prefer widely spaced crops hence while sowing optimum spacing and seed rate has to be deployed. Early planting will help in creating phonological asynchrony between susceptible stage of crop and the pest arrival. Early planted maize is less susceptible to maize earworm and stem borer, *Diatraea grandiosella* Dyar. Moreover, the female moth of *D. grandiosella* tends to lay fewer eggs on mature plants. In east Africa early planted maize tends to have a fewer infestation of leafhopper and stalk borer, *Papaipenna nebris* Guenee (Bajwa and Schaefers, 1998). Late planting of soybean interferes with colonization patterns of thrips which vectors bud blight virus. Similarly late planting of wheat helps to escape from the Hessian fly adult's oviposition as it's a pest with short life span (3-4 days). Still autumn planting is done on fly free dates in some parts of world. Planting the sugar beet crop after the migration of beet leafhopper helps in avoiding or reducing the curly top virus in beet (Norris *et al.*, 2003). Optimum input of resources like fertilizer, row spacing and irrigation will help in vigorous growth of plants while undernourished plants will be pale yellowish in colour which in turn attracts aphids (Ferro, 1996). The excessive nitrogen application in rice will lead to infestation of leaf hopper and cutworm, *Spodoptera littoralis* Boisduval. Similarly, the excessive nitrogen in other crops will invite the infestation of Tetranychus mite infestation, other sucking pest and fungal diseases. Excessive or frequent irrigation may lead to development of many soils borne disease and sucking pest infestation. The frequent irrigation in cotton will lead to luxuriant growth and it will invite insect pest infestation. Cotton bollworms are attracted to succulent vigorous growing plants therefore keeping water, fertilizer and plant density at recommended level is important to avoid rank growth. Winter irrigation will reduce 50-70% of overwintering population of pink bollworm in cotton. Frequent overhead irrigation or sprinkler irrigation will help in reducing the diamond back moth, codling moth infesting potatoes head cabbage and apple orchards. Further spider mites were found to be diminished by sprinkler irrigation at California.

5. Modern Tools and Techniques

Modern tools and techniques for insect pest monitoring and identification have significantly evolved with advancements in technology. Advancements in biosensor technology allow for the development of compact, portable devices capable of detecting insect pests or their damage in crops based on biochemical markers or physiological changes in plants. With advances in computer and machine learning, automated image recognition systems can identify insect pests from images captured by cameras or smart-phones. These systems can assist farmers and researchers in quickly identifying and monitoring pest populations in the field. There are numerous smart-phone apps available that aid in insect pest identification and monitoring. These apps often include image recognition features, pest lifecycle information and management recommendations, providing accessible tools for farmers, gardeners and pest control professionals. Recently, remote sensing techniques, such as satellite imagery and aerial drones, can provide valuable data for monitoring insect populations by identifying patterns in vegetation health and land use. Geographic information system (GIS) tools help in spatially analyzing and visualizing this data for effective pest management strategies coupled with GIS innovations in the physical traps such as pheromone traps utilize insect pheromones to attract and trap specific insect species. Also, innovations in the light trap models attract nocturnal insects using different light sources and capture them in a collection chamber. These traps are equipped with sensors for automated data collection and can provide insights into the abundance and diversity of insect populations in the deep forest or inaccessible ecosystems. Molecular Techniques such as DNA bar-coding involves sequencing a short genetic marker from a standardized region of an organism's DNA. This technique can be used for accurate species identification, even at early life stages or in fragmented specimens or fossilized samples unlike conventional taxonomy. Polymerase Chain Reaction (PCR) and other molecular techniques allow for the rapid and accurate detection of insect pests by amplifying specific DNA sequences unique to the target species. This is particularly useful in detecting invasive species or pathogens carried by insects. By integrating these modern tools and techniques into pest management practices, stakeholders can improve the accuracy, efficiency and sustainability of insect pest monitoring and identification efforts (Popescu *et al.*, 2023; Singh *et al.*, 2024).

Transgenic bio-control agents, engineered to control insect pests through genetic modification, represent a promising approach for sustainable pest management. Genes encoding insecticidal proteins, such as those derived from the bacterium *Bacillus thuringiensis* (*Bt*), are successfully introduced into transgenic plants or microorganisms. These proteins selectively target specific insect pests, providing effective pest control while minimizing environmental impact. Recently gene editing techniques such as CRISPR-Cas9 and other gene editing tools enable precise manipulation of insect genomes to introduce desirable traits, such as insecticidal proteins or traits that interfere with reproduction or development. These techniques allow for targeted genetic modifications with high efficiency and specificity. RNAi technology enables the silencing of essential genes in insect pests by introducing double-stranded RNA molecules that target specific mRNA sequences. This approach can disrupt vital physiological processes in insects, such as development, metabolism or reproduction, leading to insect mortality or reduced fitness. Advances in genetic engineering allow for the development of transgenic bio-control agents that target specific insect species or populations while minimizing off-target effects on beneficial organisms. Transgenic biocontrol agents are being engineered to carry symbiotic microorganisms that produce insecticidal compounds or interfere with insect physiology. These microorganisms can be targeted to specific insect hosts and offer long-term pest control benefits. Also, transgenic bio-control agents can be engineered to express multiple traits for enhanced pest control effectiveness or to confer resistance to multiple pest species simultaneously. This approach reduces the need for chemical pesticides and promotes sustainable pest management practices. Prior to field release, transgenic bio-control agents undergo rigorous ecological risk assessments to evaluate their potential impact on non-target organisms, ecosystem dynamics and biodiversity. These assessments help ensure the safety and effectiveness of transgenic bio-control strategies. Field trials are conducted to assess the performance of transgenic bio-control agents under real-world conditions, including their efficacy in controlling target pests, impact on non-target organisms and potential for resistance development. Long-term monitoring programs track the persistence and ecological effects of transgenic bio-control agents in the environment. By leveraging these modern tools and techniques, researchers can develop transgenic bio-control agents that offer sustainable and environment friendly solutions for managing insect pests in agriculture, forestry and public health sectors (Grilli *et al.*, 2021; Galli *et al.*, 2024).

The “Omics” approach, referring to the comprehensive analysis of various biological molecules or characteristics, such as genomics, transcriptomics, proteomics and metabolomics, can revolutionize insect pest management. High-throughput sequencing technologies, such as next-generation sequencing (NGS), facilitate the sequencing of entire insect genomes. Comparative genomics studies identify genetic variations associated with traits such as insecticide resistance, host plant preference and pathogen susceptibility. Understanding insect genomes enables the development of targeted control strategies, such as RNAi-based pesticides or gene drives. Transcriptomic analyses involve the study of gene-expression patterns in insects under different conditions, such as exposure to pesticides, host plant interactions or environmental stressors. RNA sequencing (RNA-seq.) and micro-array technologies provide insights into the molecular mechanisms underlying insect-pest interactions and identify potential targets for pest control interventions. Proteomic techniques enable the identification and quantification of proteins expressed by insects in response to various stimuli. Mass spectrometry-based proteomics and protein microarray technologies facilitate the characterization of insect protein profiles associated with traits such as insecticide resistance, detoxification mechanisms or pathogen interactions. Proteomic analyses inform the development of novel insecticides or inhibitors targeting essential proteins. Metabolomic approaches involve the comprehensive analysis of small molecules (metabolites) present in insect tissues or secretions. Nuclear magnetic resonance (NMR) spectroscopy and liquid chromatography-mass spectrometry (LC-MS) enable the profiling and quantification of insect metabolites involved in key metabolic pathways, such as detoxification, energy metabolism or pheromone production. Metabolomic studies elucidate insect physiological responses to environmental cues and identify potential targets for pest control strategies. Bioinformatics tools and databases facilitate the storage, analysis and interpretation of large-scale Omic data generated from insects. Computational methods, including sequence alignment, gene prediction, pathway analysis and functional annotation, help extract meaningful insights from genomic, transcriptomic, proteomic and metabolomic datasets. Integration of Omic data from multiple sources enables systems-level understanding of insect pest biology and the identification of novel targets for pest management. Systems biology approaches integrate Omic data with computational models to understand the complex interactions between genes, proteins, metabolites and environmental factors in insect pests. Mathematical modeling and network analysis techniques provide predictive insights into insect-pest dynamics, emergence of resistance and efficacy of control interventions. Systems biology frameworks guide the design of sustainable and context specific pest management strategies tailored to the unique characteristics of target pest populations (Kulkarni *et al.*, 2023; Singh *et al.*, 2023). RNA interference (RNAi) technology has emerged as a powerful tool for insect pest management. RNAi harnesses the natural mechanism by which cells regulate gene expression through the degradation of specific messenger RNA (mRNA) molecules, leading to the suppression of target genes. RNAi technology begins with the identification of specific target genes essential for insect survival, development or reproduction. These target genes are often involved in vital physiological processes such as digestion, metabolism or reproduction. Double-stranded RNA (dsRNA) molecules corresponding to the target gene sequences are synthesized in the laboratory. The dsRNA can be produced using various methods, including in-vitro transcription, chemical synthesis or expression in transgenic plants or microorganisms. Once synthesized, the dsRNA molecules are delivered to the target insects through different delivery methods, such as feeding, injection, topical application or incorporation into transgenic plants. Delivery methods vary depending on the insect species, developmental stage and environmental conditions. Upon ingestion or uptake, the dsRNA molecules are processed within the insect cells by cellular machinery, including Dicer enzymes, into small interfering RNAs (siRNAs) of 21-23 nucleotides in length. The siRNAs guide the RNA-induced silencing complex (RISC) to the complementary mRNA molecules, where they induce mRNA cleavage or translational repression, ultimately leading to the down regulation of target gene expression. The suppression of target gene expression/ gene knockdown through RNAi results in phenotypic effects, such as reduced viability, growth inhibition, developmental abnormalities or reproductive defects in the target insects. RNAi technology offers high specificity and selectivity in targeting insect pests, as the RNAi effect is mediated by sequence complementarities between the dsRNA and target mRNA molecules. This allows for precise targeting of pest species while minimizing off-target effects on beneficial organisms. RNAi-based approaches can be combined with other pest management strategies to mitigate the risk of resistance development. Rotating different dsRNA molecules targeting different essential genes or using RNAi in combination with conventional pesticides can delay the emergence of resistance in insect pest populations. RNAi-based insecticides are environment friendly and biodegradable, as they target specific insect pests without harming non-target organisms or causing adverse effects on the environment. RNAi technology holds great promise for sustainable insect pest management in agriculture, forestry and public health sectors, offering an effective, environmentally friendly and species-specific approach to control pest populations. Ongoing research aims to optimize RNAi delivery methods, enhance dsRNA stability and develop RNAi-based products for commercial use against a wide range of insect pests. Here are some specific examples: Control of Corn Rootworm, *Diabrotica virgifera* has been used to target genes involved in essential physiological processes of corn rootworm larvae, such as digestion or development. By incorporating dsRNA-producing transgenic plants or applying dsRNA sprays, researchers have achieved significant reductions in corn root worm populations and crop damage. RNAi-based sprays targeting specific thrips genes have shown promise in reducing thrips populations and controlling their damage to ornamental plants and vegetables. dsRNA molecules targeting mosquito genes involved in egg production, larval development or pathogen susceptibility have been delivered through transgenic plants, bacteria or viral vectors. This approach has shown efficacy in reducing mosquito populations and inhibiting the transmission of mosquito-borne diseases such as malaria, dengue and Zika virus. RNAi technology has been applied to silence tsetse fly genes associated with reproduction, energy metabolism or immune response. By delivering dsRNA via blood meals or transgenic symbiotic bacteria, researchers have achieved significant reductions in tsetse fly populations and disease transmission. Emerald ash borer is an invasive pest causing significant damage to ash trees in North America. By targeting essential genes in emerald ash borer larvae, such as those involved indigestion or detoxification, researchers aim to develop RNAi-based strategies to reduce pest populations and protect ash tree populations. These few examples show research and innovation continued to expand the applications and effectiveness of RNAi-based approaches for controlling insect pests worldwide. RNA interference (RNAi) technology has gained attention for its potential applications in pest management in India. While RNAi-based approaches are still in the research and development stage in the country, there are several ongoing initiatives and studies exploring the use of RNAi technology for pest management. While RNAi technology holds promise for pest management in India, there are also challenges and considerations, including regulatory approval, bio-safety assessments, environmental impact assessments, intellectual property rights, public acceptance and technology transfer to farmers. Continued research, investment and collaboration are essential to realize the full potential of RNAi technology in addressing pest challenges and promoting sustainable agriculture in India (Mamta and Rajam, 2017; Christiaens *et al.*, 2020; Zhu and Palli, 2020; Mehlhorn *et al.*, 2021; He *et al.*, 2022).

RNAi Technology in Insect pest management

ds RNA production

- Recombinant plasmid production.
- Mass production of recombinant plasmid inside the host cell to produce recombinant cells.
- Purification of dsRNA.

dsRNA application

- Foliar spraying
- Injection.
- Root application
- dsRNA internalization
- dsRNA integration with the host.
- dsRNA enter the insect lumen after feeding on host plant
- RNAi induced silencing complex (RISC) inside the nucleus.

Release of Insects carrying Dominant Lethal (RIDL) is a genetic engineering-based technology used in insect pest management. It involves the creation and release of genetically modified insects with a dominant lethal gene into target pest populations. In RIDL technology, insects are genetically modified to carry a dominant lethal gene. This gene is typically under the control of a regulatory sequence that ensures its expression in the target insect species. The dominant lethal gene causes mortality or sterility in the insects that inherit it. This effect can occur during specific developmental stages or throughout the insect's life cycle, depending on the regulatory elements controlling gene expression. Genetically modified insects are mass-reared in insectaries under controlled conditions. The insects are maintained, bred and selected to ensure the stability and efficacy of the desired genetic modification. Genetically modified insects are released into the environment to mate with wild pest populations. As the modified insects carry the dominant lethal gene, their offspring inherit it, leading to mortality or reduced reproductive success in subsequent generations. Through successive releases and mating with wild populations, RIDL technology can suppress target insect pest populations. The lethal gene reduces the population size, limits pest damage to crops or ecosystems and mitigates the spread of vector-borne diseases. RIDL technology offers species-specific control of insect pests, as the genetic modification is tailored to target specific pest species or populations. This specificity minimizes off-target effects on non-target organisms, beneficial insects and ecological balance. RIDL technology is environmentally friendly and compatible with integrated pest management (IPM) approaches. It reduces reliance on chemical pesticides, minimizes environmental contamination and preserves ecosystem health and biodiversity. RIDL technology can help manage insecticide resistance in pest populations by providing an alternative and sustainable approach to pest control. As the technology targets specific genes essential for insect survival or reproduction, it can overcome existing resistance mechanisms and prevent the emergence of new resistance. Before commercial deployment, RIDL technology undergoes rigorous field trials and regulatory assessments to evaluate its efficacy, safety and environmental impact. Regulatory agencies assess the potential risks and benefits of the technology and ensure compliance with regulatory requirements for environmental release. It represents a promising tool for sustainable insect pest management, offering effective, species-specific and environment friendly solutions to address global challenges in agriculture, public health and vector control. Some examples are *Aedes aegypti* mosquito control, the primary vector of the dengue virus. Some more examples are Pink Bollworm *Pectinophora gossypiella*, olive fly *Bactrocera oleae*, Mediterranean fruit fly *Ceratitis capitata*, Queensland fruit fly *Bactrocera tryoni* and the Mexican fruit fly*Anastrepha ludens*. These examples demonstrate the effectiveness of RIDL technology in insect pest management, offering targeted, environmentally friendly and sustainable solutions to mitigate the impact of insect pests on agriculture and public health (Carvalho *et al.*, 2014; Slade and Morrison, 2014; Schwindenhammer, 2020).

6. Technological Development

6.1. Pest Monitoring and Identification

AI-powered smartphone apps have the potential to prevent or minimize pest outbreaks by alerting farmers and accelerating illness diagnosis. Even though farmers in many developing nations lack access to these sophisticated instruments, new solutions for infield crop pest diagnosis are made possible by growing Internet penetration, smartphone usage and offline simulations Example: “eSAP” application developed by University of agricultural sciences, Raichur, Karnataka is an offline program that creates expert connections and produces audiovisual reports in real time to aid with prompt decisionmaking. Another automated method of pest monitoring is use of sensors where it records and validates the wing beat harmonics, flight direction and melanisation. Based on noise analysis that insects make, acoustic approaches can allow quick, noncontact and real-time identification of these insects. Numerous acoustic sensor types, including accelerometers, piezoelectric sensors, microphones, geophones, ultrasonic transducers and Doppler vibratometers, can be used depending on the target insects and field conditions.

6.2. Drone Applicators

Many studies have highlighted that between 2013 and 2018, 442 farmers were killed due to their exposure to chemicals. The use of drone technology reduces the need for chemicals and saves labour, time and water. Additionally, it reduces human exposure to chemicals and minimizes their use. By integrating drone technology with artificial intelligence (AI), machine learning and the Normalized Difference Vegetation Index (NDVI) to obtain accurate plant health information and guarantee necessary chemical application, these problems can be resolved (Katekar and Cheruku, 2022).

6.3. Precised Applicators

Accurate pesticide application is made possible by the variable-rate automated spraying technology, which collects data on pest severity, crop canopy and pest density. With the collected data, precised spot spraying is achieved. It has been found that there has been considerable decrease in the amount of insecticides used on maize and soybean crops and when compared to the cost of applying pesticides across the entire area, the crop cost reduction achieved using this method was 56.16%.

6.4. IoT Devices

Internet of Things includes two components: the hardware (the plant protection device) and the software (information management system). They are equipped with many sensors and the software component will provide mobile SMS services to the respective farmer/extension officer ensuring the need-based pest control strategy.

Eventually, all the advantages of technological developments enable more efficient, target specific care. In addition to shielding the environment from danger, pest control measures may prevent needless harm to plants, animals and wildlife with focused treatments. This results in a more environment friendly and sustainable solution that benefits the environment over time.

7. Future Prospects

In the current scenario, pest management strategies need to be geared up with progressing technological interventions. The present pest management approaches have to be upgraded for meeting the future needs and achieving more sustainability. The concerns are growing towards health and hygiene. Ecologically sound and environmentally safe pest management methods are immediate needs. Ecological engineering approach needs to be contemplated with the aim of gaining further insights. The present IPM principles may be turned to the angle of total system approach with holistic view. Innovation is being felt for development of organic nano-pesticides which can replace the traditional ones. Research and development towards novel low-dose insecticide molecules need critical thrust. Plant and microbes driven insecticides and bio-control aspects needs further research considerations. Developing of synthetic analogues of known molecules/ plant essential oils with insecticidal property could reduce manufacturing cost with greater stability of the compound. Cutting-edge biotechnological tools may boost the development of transgenic crops. Incorporation of resistance in the host plant may be achieved through the gene editing technique. Deployment of automated techniques for pest management in agro-ecosystems is nascent but emerging with pace. IoT (Internet of things), like sensors, can detect the presence of insect-pests in specific spots where drone applicators can make targeted spray, optimizing the use of insecticides. Developing Artificial Intelligence (AI) based forecasting system for specific insect pest is a field with tremendous scope. The core of the future research and development lies in the sustainability of the system and will of course remain the prime concern.

8. Conclusion

The existing pest management strategy has to be forged in order to gain and maintain sustainability in agro-ecological system. All efforts have to be made placing the sustainability of the agricultural system as the central idea. Emphasis has to be more on designing cost-effective, ecologically sound and environmentally safe pest management strategies. Health, hygiene, resistance, resurgence are aspects to be seen while developing any management technique. Resource conservation is another substantive concern where quality of natural resources like soil, water, natural enemies, pollinators, humans and animals has to be considered while developing a quality management strategy. Many of the present management tools, instead solving the purpose, have exacerbated the pest problem, created ecological imbalance, polluted the environment and caused several health concerns. Utilization of knowledge and technology from different fields like artificial intelligence, automated system, information technology, ecological aspects, chemical ecology, gene-editing, host plant resistance, pest-parasitoid/ predator interaction, new generation insecticides, bio-pesticides, pest surveillance and forecasting system *etc*. needs further in-depth research and are needed to be utilized to their maximum. Availability of developed technologies with stakeholders and farmers along with their execution at ground level is equally important, therefore, designing robust extension functionary is important tool to conquer the ultimate win.

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