Innovative Approaches in Pest Management

Sneha Sharma, Tanusree Ghosh, Rittik Sarkar, Chethankumar M, Vishaw Deep Sharma

As the pest population is rising, the impact of an over-reliance on pesticides has made sustainable and innovative pest management more important. This review will draw attention to present developments in pest management technology which improve the productivity of pest control, particularly those that allow reduction of the eco-invading impact of pest control. Precision agriculture equipment including Unmanned Aerial Vehicles (UAVs)/drones, Remote sensing, Machine Learning (ML), Geographic Information System (GIS), Artificial Intelligence (AI) and Internet of Things (IoT) based surveillance systems for pest identification and interventions early in their life cycle. A discussion of semiochemical-based technologies (SPLAT), nanotechnology-enabled pesticide formulations, and botanical and essential oil based nanoformulations that enhance stability, controlled release and efficacy of actives is also included in the review. They examine novel strategies and approaches of storing grain and managing pests within storage facilities, which include hermetic storage systems, innovative smart packaging system and use of AI in pest monitoring. They compare biotechnological methods including transgenic crops, gene silencing, gene transformations, lectins approaches, proteins inhibitors as possible ways to help us control the pests sustainably. These Integrated pest management (IPM) will assist us in promoting sustainable, ethical and resilient systems in agriculture.

Keywords: *Precision agriculture, Biotechnology, IPM, Innovative tools, Drones*

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Introduction

Since the dawn of agriculture, there has always been a link between agriculture and pest problems and protection of crops has been a constant challenge. Pests are still impacting major losses in different cropping systems. They pose a threat not only to field crops, but to livestock as well as held agricultural products. This puts the productivity and food supply at risk. Insect pests, weeds and plant diseases account for an estimated 40% annual loss in global food production. Better handling of pests is the major cause for this loss (Srishailam et al., 2022). Such losses are not only of agricultural production but also, of food and nutritional security in the world. They create the difficulties in implementing SDG 2 which is related to ending hungry and malnutrition (Martos et al., 2021). In this scenario, food production stability is a major scientific and policy issue all over the world. Synthetic pesticides are widely employed over the years could deal with losses resulted from the pests.

Its misuses created so many of the severe problems including alterations of natural enemies, pests resistance, contamination of environment, reduced biodiversity, human health hazards etc. These problems clearly show the failure of chemical method of pest control and indicate importance of the gentle approach to control pests. So, to overcome these challenges new methods and sustainable control have emerged, which are displacing the traditional chemical approaches, the IPM strategy and the newest pest management strategies utilizing innovative technologies. All these are aiming at minimizing the use of chemicals and increasing the efficacy of total pest control efforts, and improving the status of ecological and environmental condition. Development and utilization of new pest management techniques are crucial to deal with today's agricultural challenges and for achieving sustainable agriculture.

Precision Agriculture and Digital Pest Management Tools

Drones for Precise Pesticide Application

Aerial technology, commonly recognised as a drone (UAV), is a novel and revolutionary technology tool that can be used in plant protection within precision agriculture. Real time aerial monitoring makes it possible to evaluate and respond quickly to pest infestations, which helps farmers to implement pest management at right time. Precision farming with drones helps farmers save costs and contribute to sustainability (Singh and Singh, 2025). These airborne tools use high-resolution imaging and autonomous flight patterns to minimize human exposure to hazardous materials and optimize resource allocation (Dey et al., 2025). Drone sprayers, an important cornerstone of climate-resilient farming, can reduce pesticide consumption, reduce spray drift by 60% and boost yields by 12-20% based on crop variety and field conditions (Borah et al., 2025). Manual application of pesticides in rice fields can be limited by muddy conditions, dense crop canopy and the difficulty in accessing pests at the bottom of the plant at the later growth stages (Sheng et al., 2002). On the other hand, drone application of pesticide can allow for precise aerial spraying, alleviating labour dependence, and enhancing spray coverage and the mixture of chlorfenapyr, chlorantraniliprole, and lufenuron resulted in a control efficacy of 94.94%, and reduced the population of *Spodoptera frugiperda* by 94.86% (Song et al., 2020). Drone technology is being highlighted as an innovative pest management tool, to enhance pest control methods like the Sterile Insect Technique (SIT) and mating disruption. The integration of autonomous navigation and image processing systems with Drone Sprayers represents a major step in precision agriculture, providing efficient automation solutions for adjusting spray parameters and guaranteeing even delivery of chemicals with minimal drift (Singh et al., 2024). In vineyards, image-based analysis has proven to be useful when fine-tuning UAV spray application to improve droplet deposition and reduce off-target spray losses, especially when optimizing flight pattern, nozzle type and travel speed (Biglia et al., 2022).

Eyes in the Sky: Remote Sensing and GIS-Based Pest Surveillance

Remote sensing (RS) refers to the science and technology of acquiring information about objects, areas or phenomena from a distance, using sensors and imaging devices that analyse reflected or emitted energy (Lillesand et al., 2015). The applications of RS are wide-spread encompassing various emerging technologies such as satellites, Geographic Information Systems (GIS), Internet of Things (IoT), cloud computing, sensors, and Decision Support Systems (DSS) (Aziz et al., 2025). Researchers can also monitor slight changes in plant health using satellite sensors such as Sentinel-1 and Sentinel-2, or with high resolution multispectral cameras on UAVs (Saran et al., 2025). This early detection capability helps facilitate “scout and treat” strategies by allowing the application of pesticides in hot spots, rather than whole field spraying. Crop stress due to pests and diseases can be detected through remote sensing, which can identify shifts in the colour, shape and photosynthetic activity of a crop and cause changes in the crop's spectral reflectance (Prabhakar et al., 2012). Spatiotemporal remote sensing plays a crucial role in monitoring evapotranspiration, soil moisture dynamics, and crop stress, enabling optimized irrigation and pesticide application in hilly terrains (Chandel et al., 2021). Using satellite-based remote sensing, it identified the optimal management period for cotton leafworm (*Spodoptera littoralis*) by estimating degree days from air temperatures ranging between 174.85 and 197.59. Similarly, Nansen et al. (2015) demonstrated that temporal variations in body reflectance patterns of maize weevil (*Sitophilus zeamais*) and large black flour beetle (*Cynaeus angustus*) were associated with their responses to entomopathogenic nematodes (EPNs) and insecticidal plant extracts.

Artificial Intelligence and Machine Learning: Reactive to Proactive Pest Management

In recent times, digital technologies like the Internet of Things (IoT), Artificial intelligence (AI), and Machine learning (ML) have revolutionized the agriculture sector, resulting in “Agriculture 4.0” (Araujo et al., 2023). Conventional extension methods have been reinforced with the use of digital technologies, which spread location-specific and sustainable management practices. In addition to pest identification, AI fusion models use information from soil sensors, climate data and seasonal variables to create sophisticated prediction systems. These predictive methods enable interventions to be implemented at the right time and in the right place, enhancing overall crop productivity and reducing environmental impacts (Saran et al., 2025). With AI-powered mobile apps, farmers can upload photos of infested crops and receive instant recommendations for pest management. The use of Plantix, riceXpert and FarmRise are examples of applications that assist in diagnosing pest issues in the field and give advice on IPM (Iost Filho et al., 2022). IoT based UAV system integrated with AI algorithms and Python based frameworks have been designed to take pictures of the rice pest and upload them to cloud applications like Imagga Cloud (Yadav et al., 2024). The abundance of diamondback moth populations on cabbage crops was predicted using deep learning approaches (Kaur et al., 2022).

Semiochemical-Based Technology

SPLAT (Specialized Pheromone and Lure Application Technology)

SPLAT, developed by ISCA Technologies, is a controlled-release emulsion technology for delivering of semiochemicals, phagostimulants, and pesticides under diverse environmental conditions. It functions as a matrix-type or monolithic diffusion-controlled release system. Active ingredient is embedded within a carrier matrix to ensure gradual and prolonged dispersion from two weeks to six months (Pawar et al., 2022). In Bt cotton, using SPLAT-PBW at a rate of 1250 g/acre resulted in a notable decline in the number of male moths and damage to bolls. For brinjal, applying 500 g/acre of SPLAT-BSFB effectively reduced damage to shoots and fruits. Similarly, SPLAT-MAT spinosad ME was effective in managing fruit flies throughout the entire growing season in mango orchards, eliminating the need for lure replacements and demonstrating high efficiency and it is cost-effective. The efficacy of SPLAT-YSB was encouraging against YSB infestation in rice and SPLAT-Tuta was effective against *Tuta absoluta* by significantly reducing both leaf and fruit damages (Badari et al., 2023). The targeted applications demonstrate the versatility and effectiveness of SPLAT as a sustainable management tool in IPM of important agricultural pests, as a replacement for conventional chemical control**.**

Nanotechnology-based Formulation in Pest Management

There are some disadvantages to conventional pesticide formulations such as spray drift, use of hazardous solvents and inefficient dispersion. In addition, the excessive and indiscriminate use of synthetic pesticides leads to increased resistance in insect pests, pest outbreaks, ecological imbalance, environmental pollution and even the potential risk to human health (Raju, 2019). In this context, nanotechnology is a potential approach to mitigate pest infestation, which can increase the efficiency of the active substance, decrease the amount of chemical input and lower the total production cost (Wang et al., 2022). It includes the process of converting the active ingredients into nanoparticles (NPs) with a larger surface area and better contact efficiency with the target surfaces. The benefits of these attributes make nanopesticides more viable for adoption, as they release the pesticidal product in a controlled manner, result in lower volatilization rates, high adsorption to target, good tissue penetration, and do not lead to residue accumulation and environmental contamination (Kannan et al., 2023). The commonly used nano-based pesticide formulations include nanoparticles (NPs), nanoemulsions, nanocapsules, nanosuspensions, nanogels, and nanospheres. These are extensively used in the management of pests and diseases (Kariyanna et al., 2025). The addition of nanoparticles containing a hormone, coating with insecticide or tagging them with DNA has been investigated for the effective management of insect pests (Chowdappa et al., 2013. The *Bacillus thuringiensis* Cry11Aa toxin was protected from UV degradation by coating with Mg $(OH)_2$ nanoparticles. Moreover, the tripolyphosphate crosslinked chitosan nanocarriers have demonstrated promising results, for the botanical pesticide PONNEEM exhibited 90% larvicidal efficacy and 88% antifeedant effect against Helicoverpa armigera (Kumar et al., 2019). Enhancing foliar wettability and photostability and improving the pest control efficacy, nanogel-encapsulated lambda-cyhalothrin (LC@TNPE) performed better than conventional commercial formulations (Shen et al., 2022).

Improved formulations of Essential oil and botanicals

Botanical and essential oil (EO) based insecticides are well known to be eco-friendly alternatives with broad spectrum activity and low environmental effect. Despite their advantages, their potential use on a large scale is hindered by a number of challenges, including rapid photodegradation, thermal instability, and high volatility, which collectively compromises their persistence and effectiveness in field conditions (Damalas & Koutroubas, 2020). To overcome these limitations, advanced formulation techniques like microemulsions, nanoemulsions, microencapsulation and nanoencapsulation were developed to increase the stability, solubility and bioavailability of the active compounds (Jerobin et al., 2012).

The physicochemical properties, including droplet size, zeta potential (measure of the surface charge of particles in nanoemulsions (NE), microemulsions (ME), and encapsulated systems), and encapsulation efficiency, play a key role in determining the performance of these advanced formulations (Rasmussen et al. 2020). Research on nanoemulsions derived from *Azadirachta indica*, *Eucalyptus globulus*, has shown improved insecticidal activity and slower degradation under field conditions compared with conventional bulk emulsions (Adak et al., 2020). Huang et al. (2024) used a star polycation (SPc) nanocarrier to encapsulate Camptothecin (bioactive compound derived from the Chinese medicinal plant *Camptotheca* *acuminate*), enhancing its stability under alkaline conditions and showing strong ovicidal and larvicidal activity against *Spodoptera frugiperda*. Recent studies have also emphasized the use of natural surfactants such as gum arabic and alkyl polyglycosides, as well as biopolymer-based materials like lignin and chitosan, for developing biodegradable and environmentally safer carriers that help reduce formulation costs and associated risks (Mossa et al., 2022).

Stored Grain Pest Management: Modern Storage and Packaging Innovations

Pest management plays an important role in achieving food security and contributes to economic development and food safety. Pest problems have grown to be a serious problem in food storage, limitations of traditional chemical control solutions and new emerging issues like climate change and pesticide resistance have led to the development of new food storage structures, packaging and traps. The main efforts being made by the Indian researchers and engineers are in developing the storage that is pest resistant like the SuperGrainbags (Mishra et al., 2024) which are metal silos. Hermetic storage is an advanced technique for the long-term storage of grain that relies on having a low-oxygen environment and a sealed storage structure to ensure a longer shelf life and quality. It works by controlling the conditions in which these components are stored, using the material used in their packing which has extremely low oxygen permeability (Okolo et al., 2017). The hermetic storage methods include GrainPro, PICS (Purdue Improved Crop Storage), and UAF (University of Agriculture Faisalabad) bags, which are commonly used in developing countries. (Oyewole et al., 2025) Biopesticides for use in active packaging offer anti-fungal, insecticidal, repellent and herbicidal properties, making them a new option for food preservation systems (Sousa et al., 2023). A double-layered packaging system was designed by Soujanya et al., 2018 with incorporation of rice seed and especially, between two plastic layers and the application was made of *Tinospora cordifolia* leaf powder containing biopesticides, effective pest control was reported and further it was suggested that the system can be widely applied for biopesticide-based packaging systems. Smart storage systems combine IoT sensors and artificial intelligence (AI) algorithms, which allow for real-time, continuous temperature and humidity monitoring leading to better management of the grains. The system can also automatically react to the humidity, tuning it accordingly in case there is a need for optimal storage conditions (Sharma & Shivandu, 2024).

Application of Biotechnological Approaches in Insect-Pest Management

Bioinsecticides are extremely beneficial when enhanced by Biotechnology. It also creates a larger market potential. Insect pest management is a component of biotechnology methods, such as genetic engineering, genome editing and others. These approaches promote sustainable agriculture and help decrease the reliance on harmful chemical pesticides. A detailed discussion of these methods is given below:

Gene Transformation

The process of genetically modifying crops for improved insect resistance involves incorporating a specific DNA segment or gene into plants to protect them from insect threats. The added DNA segment typically produces a protein that possesses insecticidal properties. Resistance in plants is achieved through the expression of insecticidal proteins produced by the introduced gene segment (Gatehouse, 2013). This technology has been tested against a broad range of insect pests belonging to the orders Lepidoptera, Coleoptera, and Diptera (Birkett and Pickett, 2014).

Genetically modified crops producing insecticidal proteins from *Bacillus thuringiensis* (Bt), a soil bacterium, have been widely used in agriculture worldwide since their introduction in 1996 (Abbas, 2018). The *cry* gene transformation technology involves transferring selected DNA sequences or genes into crop plants through *Agrobacterium* mediated transformation or particle bombardment methods (Juturu et al., 2015).

Apart from Bt technology, several additional strategies have been investigated for protecting plants from insect attack. Lectins, naturally present in many plants, bind to carbohydrates in the midgut of phytophagous insects and disrupt their digestive system (Vandenborre et al., 2011). Transgenic approaches have also been used to introduce protease inhibitors, which prevent insects from properly digesting food (Singh et al., 2020). In the same way, genetically engineered plants that generate alpha-amylase enzyme antagonists are being created to offer defense against insects categorized as Lepidopteran, Coleopteran, Dipteran, and Hemipteran. In addition, chitin present within the external skeleton and gut lining of insects is degraded down by insect chitinase enzymes and chitinase-like proteins. Insecticidal response has already been demonstrated by successfully cloning the genes producing these proteins into plants. Below is a detailed discussion of each of these tactics and their function in managing insect pests.

Cry Genes

Insecticidal crystalline proteins (ICPs), which are toxic to insects, are produced by the gram-positive soil bacteria *Bacillus thuringiensis (Bt).* Genes which are responsible for encoding these types of proteins mainly parasporal crystal protoxins, which provide resistance against many insect pests mainly lepidoptera (García-Cruz et al., 2026). In the alkaline environment of the insect larval midgut, these crystal proteins dissolve and become protein proteolytically activated, functioning as protoxins. The active toxins then bind to certain receptors on the midgut's epithelial cells, leading the cell membrane to become perforated. As a result, gut paralysis occurs within two to three days, which stops feeding activity and eventually causes larval death (Kumari et al., 2022).

Table 1. Transgenic crops with insect-resistant Bt genes

S.no.	Target insects sp.	Target crop	Transgene
1	*Tuta absoluta*	Tomato	cry1Ac
2	*Chilo suppressalis*	Rice	cry1A(b)
3	*Scirpophaga incertulas*	Rice	cry1A(c)
4	*Scirpophaga incertulas*	Rice	cry1A(b)/cry1A(c)
5	*Cnaphalocrocis medinalis, Scirpophaga incertulas*	Rice	cry2A/cry1A(c)
6	*Helicoverpa armigera*	Cotton	cry1Ab + NptII, cry2AX
7	*Helicoverpa armigera*	Pigeon pea	Cry1AC+cry2Aa
8	*Helicoverpa armigera*	Chickpea	CryIIAa
9	*Cnaphalocrocis medinalis*	Rice	cry2A
10	Cnaphalocrocis medinalis	Rice	Cry1A(b)
11	*Anthonomus grandis*	Cotton	Cry1Aa
12	*Helicoverpa armigera*	Pigeon pea	Cry2Aa
13	*Scirpophaga incertulas, Cnaphalocrocis medinalis*	Rice	cry2AX1

14	*Spodoptera litura*	Cotton	cry1Ab + cry2Ac
15	*Holotrichia parallela*	Soyabean	cry8-like
16	*Achaea janata,* *Spodoptera litura*	Castor	cry1Ac
17	*Helicoverpa armigera*	Cotton	cry2AX1
18	*Tuta absoluta*	Tomato	cry1Ab

Genes for Vegetative Insecticidal Proteins (VIP Gene)

Bacillus thuringiensis (Bt), a bacterium found in a range of environmental conditions, has inherent antimicrobial qualities against numerous economically important agricultural-related insects. This insecticidal activity is mainly due to the production of different proteins during various growth stages of the bacterium. Among these proteins, the Vegetative Insecticidal Proteins (Vip proteins) are one of the most important groups. These proteins are synthesized during the vegetative growth phase and are considered highly effective toxic agents because they differ from Cry proteins in sequence homology and receptor-binding sites (Gupta et al., 2025). There are actually three main subfamilies of VIP proteins. As heterodimer poisons, Vip1 and Vip2 are most effective against insect pests that belong to the orders Coleoptera and Hemiptera. In contrast, Vip3 proteins, which are the most extensively studied group, show strong toxicity against Lepidopteran pests. Vip proteins are often referred to as second-generation insecticidal proteins because they can be used either independently or together with Cry proteins for controlling a wide range of insect pests (Gupta et al., 2021). To overcome pest resistance and delay the evolution of resistant insect populations, Vip3 proteins have been successfully pyramided with Cry proteins in transgenic crops such as maize and cotton (Syed et al., 2020).

Table 2. The role of Vip genes in different crop species

S.no.	Target insect sp.	Target crop	Transgene
1	*Heliothis sp.*	Cotton	cry1Ab + Vip3A
2	*Maruca vitrata*	Cowpea	Vip3Ba1
3	*Helicoverpa armigera*	Cotton	Vip3AcAaa (Vip3Aa1 + Vip3Ac1)
4	*Chilo infuscatellus*	Sugarcane	Vip3A

Lectins

Lectins are entomotoxic proteins present in many plant species that bind to carbohydrates and exhibit insecticidal properties. Lectins obtained from different plant species and sources have been reported to be toxic against several economically important insect pests belonging to the orders Lepidoptera, Coleoptera and Homoptera these proteins have negative effect growth and development of insects by causing larval weight loss, reduction in feeding activity, suspending adult emergence, increasing the developmental stages of insect, and increasing insect death rates (Mishra et al.,2022).

Table 3. Lectin Gene Expression for Protection Against Insect Pests

S.no.	Target insects sp.	Target crop	Transgene
1	*Sitobion avenae*	Wheat	Snowdrop lectin (Galanthus nivalis agglutinin; GNA)
2	*Eoreuma loftini*	Rice, Sugar	Snowdrop lectin

3	*Lacanobia oleracea*	Tomato	GNA-neuropeptide-allatostatin
4	*Myzus persicae and Nilaparvata lugens*	Potato, Rice	GNA-spider-venom toxin I (SFI1)
5	*Sitophilus zeamais*	Stored grains	M. urundeuva leaf lectin (MuLL)
6	*Myzus persicae* and *Sitobion avenae*	Potato	Hv1a/GNA
7	*Myzus persicae*	Potato	Galanthus nivalis agglutinin (GNA)
8	*Sitophilus zeamais*	Stored grains	Schinus terebinthifolius leaf lectin (SteLL)
9	*Lipaphis erysimi*	Mustard	Colocasia esculenta tuber agglutinin (CEA) + Galanthus nivalis agglutinin (GNA)
10	*Schizaphis graminum,*	Wheat	Pinellia pedatisecta agglutinin (PPA)
11	*Spodoptera litura*	Cotton	Insect gut binding lectin from Sclerotium rolfsii
12	*Callosobruchus sp.*	Cowpea	Arcelin from Phaseolus vulgaris

Fusion Proteins

The main reason for creating fusion proteins is to address the potential constraints of traditional transgenic insect pest management strategies. This is a technique of multiple transgene(s) in a transgenic plant and combines several hybrid poisons against insect pests (Liu et al., 2017). Two or more insecticidal proteins are put together into an individual protein molecule to create fusion proteins. Therefore, these proteins are formed through the integration of different insecticidal proteins to enhance pest control efficiency (Keerthana el al.,2026).

Table 4. Crop plants using Fusion Proteins to Combat Insects

S.no.	Target insects sp.	Target crop	Transgene
1	*Scirpophaga incertulas,*	Rice	cry2AX1
2	*Lygus spp.*	Cotton	cry51Aa2
3	*Spodoptera exigua, Harmonia axyridis*	Maize	cry1Ab/cry2Aj
4	*Spodoptera litura, Ostrinia nubialis*	Cotton	cry1Be + cry1Fa
5	*Cnaphalocrocis medinalis,*	Rice	cry1AC + ASAL
6	*Ostrinia furnacalis, Cnaphalocrocis medinalis*	Rice	cry1Ab + vip3A
7	*Chilo suppressalis*	Rice	cry2Aa + cry1Ca
8	*Helicoverpa armigera, Spodoptera litura*	Cotton	cry2Ab + cry1F + cry1AC
9	*Scirphophaga excerptalis*	Sugarcane	cry2Aa + cry1Ca, cry1Ab + cry1Ac

Protease Inhibiting Factors

By preventing the function of digesting proteases, plant-based substances known as protease inhibitors (PIs) obstruct insect pest ability to digest food. These inhibitors suppress insect digestive enzymes by blocking proteolysis result in absence of essential amino acids, eventually decreases fertility, boosts mortality, and expands the developing time (Paul et al., 2024). Serpins and cystatins are two of the several plant protease inhibitors that have been thoroughly researched for their potential to control insect pests. Serpins are irreversible inhibitors of serine proteases. Insect orders including Diptera, Lepidoptera, Orthoptera, Coleoptera, and Hymenoptera frequently include serine proteases. On the other hand, the most common digestive enzymes present in Hemipteran and Coleopteran insects is cysteine proteases, and their function is effectively inhibited by cystatin proteins (Trembly et al., 2022).

Table 5. Expression of Insect Resistance-Related Protease Inhibitor Genes

S. no.	Target insect sp.	Target crop	Transgene
1	*Sesamia inferens*	Rice	Potato proteinase inhibitor II
2	*Sitotroga cerealella*	Wheat	Barley trypsin inhibitor

α-Amylase Inhibitors

In insects, the digestive enzyme α-amylase plays an important role in the breakdown and digestion of carbohydrates. α-Amylase inhibitors interfere with insect digestion by blocking the activity of the α-amylase enzyme. Various types of α-amylase inhibitors present in plant seeds and vegetative parts have been reported to effectively control many phytophagous insect pests (Franco et al., 2025).

Table 6. Expression of α-Amylase Inhibitor Genes for Insect Resistance

S.no.	Target insects sp.	Target crop	Transgene
1	*Callosobruchus maculatus*	Cowpea	αAI-Cp
2	*Spodoptera spp.* and *Agrotis spp.*	Tobacco	αAI-Ta
3	*Chilo partellus*	Maize	αAI

Chitinase in Insects

Chitin may be broken down or inhibited by insect chitinases, which are hydrolytic enzymes. The primary structural element of the insect's peritrophic membrane and exterior skeleton. It provides protection against harsh environmental conditions, mechanical damage, and natural enemies (Chen et al., 2018b). The degradation of chitin is an important step throughout the phase of ecdysis which is the periodical removal that occurs in the previous cuticle layer.

Chitinases are produced by various organisms, including plants that do not contain chitin, where they function in recognizing and degrading chitin present in insect pests (Oyeleye & Normi, 2018). The transgenic expression of chitinase enzymes has been proposed as an effective strategy for crop protection. The role of chitinase in insect pest management has been investigated in several insect species such as silkworm Bombyx mori, rice brown planthopper *Nilaparvata lugens*, cotton mealybug *Phenacoccus solenopsis*, and rice striped stem borer *Chilo suppressalis*, transgenic maize plants expressing chitinase genes have shown enhanced resistance against corn borer (*Sesamia cretica*) (Osman et al., 2016).

Genome Editing

Genome editing, also known as gene editing, is an advanced biotechnology technique used to insert, delete, replace, or modify DNA sequences at specific locations within the genome in order to alter gene function through the cell's natural repair mechanisms (Bortesi & Fischer, 2015). This technology has emerged as an important tool in insect pest management due to the increasing development of insect resistance against Bt traits, which poses a major challenge to agricultural productivity. Genome editing provides a novel, cost-effective, precise, and environmentally friendly approach for improving pest resistance in crops. It is widely recognized as a modern scientific method for modifying the DNA of living organisms (Belfort & Bonocora, 2014). Many genetic modification methods are accessible, such as TALENs (transcription activator-like effector nucleases), (CRISPR/Cas9) clustered regularly interspaced short palindromic repeats and (ZENs) zinc finger nucleases, these are among the most widely utilized in pest management.

Table 7. CRISPR/Cas9 Technology is used to Engineer Insects for Pest Management

S.no.	Target insects sp.	Target Gene
1	*Tribolium sp.*	EGFP and E-cadherin gene
2	*Plutella xylostella*	Abdominal-A homeotic gene (Pxabd-A)
3	*Drosophila melanogaster*	Chitin synthase 1
4	*Agrotis ipsilon*	Yellow-Y gene
5	*Locusta migratoria*	Odorant receptor co-receptor (Orco) gene
6	*Spodoptera litura*	Abdominal-A (Slabd-A) gene
7	*Spodoptera littoralis*	Olfactory receptor co-receptor (Orco) gene
8	*Helicoverpa armigera*	HaCad
9	*Spodoptera exigua*	Ryanodine receptor
10	*Ceratitis capitata*	Eye Pigmentation Gene White Eye (We)
11	*Helicoverpa armigera*	Tetraspanin
12	*Plutella xylostella*	PxABCC2, PxABCC3
13	*Helicoverpa armigera*	α-6-nicotinic acetylcholine receptor (nAchR)
14	*Rhopalosiphum padi*	β-1-3 wangin maize
15	*Ostrinia furnacalis*	ABCC2

RNA Interference (RNAi) for Pest Management

RNA interference (RNAi) is a molecular technique used to reduce or suppress the expression of specific genes in an organism. It is also known as post-transcriptional gene silencing (PTGS). This process works through the introduction of double-stranded RNA (dsRNA) into cells, which leads to the silencing of targeted undesirable genes (Kamthan et al., 2015). RNA interference is a natural process where the expression of specific gene is silenced or stopped by using dsRNA. In insect pest management these dsRNA artificially introduced in the insect cell the insect body cell treated it as an unwanted virus particle and which activated the RNAi pathway that shut down the target gene and insect fail to survive. (Katoch et al., 2013). It is most effective approach that have tendency to create new aspects for environment friendly management practices and sustainable pest management strategies exclusively for sap sucking insect pests.

Table 8. RNAi-Based Insect Pest Management Strategies

S.no.	Target insects sp.	Target Crop	Silenced gene
1	*Diabrotica v. virgifera*	Corn	Destruction of target mRNA
2	*Diabrotica v. virgifera*	Corn	Brahma (brm) gene, hunchback (hb)
3	*Leptinotarsa decemlineata*	Potato	β-actin gene
4	*Lepidopteran*	Maize	dsRNA-Spray
5	*H. armigera*	Tomato, Tobacco	Chitinase gene-HaCHI

6	*C. suppressalis*	Rice	Aminopeptidase N genes APN1+APN2
7	*Leguminivora glycinivorella*	Soybean	SpbP0-dsRNA
8	*Helicoverpa armigera*	Cotton	Juvenile hormone methyl transferase (JHMT)
9	*Diabrotica virgifera virgifera LeConte*	Maize	Dvvgr, dvbol
10	*Leptinotarsa decemlineata*	Potato	ECR gene
11	*Scirpophaga incertulas*	Rice	AchE-Acetylcholine esterase
12	*Manduca sexta*	Tobacco	v-ATPaseA gene
13	*Bemisia tabaci*	Tobacco	BtACTB gene
14	*Aphis glycines*	Soybean	TREH, ATPD, ATPE, CHSI
15	*Bemisia tabaci*	Tobacco	Phenolic glucoside malonyltransferase
16	*Spodoptera littoralis*	Tobacco	Sl 102 immune gene

Conclusion

Improvements in newly developed pest management technologies are accompanying a new era in farming system. The use of resources has been optimized to combat the pests, with the help of modern technologies as drones, satellite technology, artificial intelligence, machine learning and IoT based systems, limited use of traditional pesticides and with a longer lasting effect. In addition, semiochemicals, nanotechnology, innovative botanicals methods and storage innovations are effective and eco-friendly technologies for suppressing pests. Other tools of biotechnology that allow to produce pest-resistant varieties with sustainable crop protection measures are genetic engineering, genome editing, RNA silencing and marker-assisted breeding. While there are obstacles to overcome based on the cost, regulation, and resistance management, the application of these new technologies in pest management can offer great promise to improving agricultural productivity, protecting ecosystems, and fortifying long-term food and nutrition security. These transformative strategies will significantly contribute to improving agricultural productivity and sustainability, protecting the environment, and ensuring food and nutritional security.

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