Pest Management in Crops and Stored Grains

Editors

Ms. Aishwarya Anant Chavan
Ph. D. Scholar,
(Agril. Entomology),
Mahatma Phule Krishi Vidyapeeth, Rahuri

Dr. Yasmin
M.Sc., Ph.D.,
Assistant Professor,
Department of Agricultural Engineering,
V.S.B College of Engineering Technical Campus,
Coimbatore - 642109

Dr. Satya Narayan Satapathy
Associate Professor,
Department of Entomology,
Faculty of Agricultural Sciences (IAS),
Siksha 'O' Anusandhan,
(Deemed to be University), Bhubaneswar, Odisha

Mr. Chandan Kumar Panigrahi
Ph.D. (Agri.) Scholar,
Department of Entomology,
Faculty of Agricultural Sciences,
SIKSHA 'O' ANUSANDHAN,
Deemed to be University,
Bhubaneswar - 751029, Odisha.

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About The Editors

Aishwarya Anant Chavan completed her B. Sc. (Agriculture) and M. Sc. (Agril. Entomology) from DBSKKV, Dapoli, and is currently pursuing her Ph. D. (Agril. Entomology) from Mahatma Phule Krishi Vidyapeeth, Rahuri. She has cleared ICAR ASRB-Net exam. In her achievements, she was awarded as Outstanding Researcher Award and Young Entomologist Award in 2025. She has published research articles, book chapter and attended training and workshop in the field of Agril. Entomology. She also presented her work through oral presentations at national and international conferences.

Dr. A. YASMIN is currently serving as an Assistant Professor and Assistant Head of the Department of Agricultural Engineering at V.S.B. College of Engineering Technical Campus, Coimbatore. She holds a B.Sc. in Agriculture from Agricultural College and Research Institute, TNAU, Coimbatore, and M.Sc. in Agricultural Entomology from Agricultural College and Research Institute, TNAU, Madurai and Ph.D. (Entomology) from Agricultural College and Research Institute, TNAU, Madurai. Her research expertise includes formulation of botanical pesticides, integrated pest management and storage entomology. She has published research articles; book chapters related to agricultural entomology and participated in national and international conferences. In addition to her academic contributions, she has also published patents in the field of Agricultural Engineering, demonstrating dedication to pioneering solutions and tangible progress in the field of agriculture

Dr. Satya Narayan Satapathy is presently working as Associate Professor (Entomology) at Faculty of Agricultural Sciences (IAS), Siksha ‘O’ Anusandhan (Deemed to be University), Bhubaneswar, Odisha. He is life member of five scientific societies in the field of Entomology. He is also Assistant editorial member of two peer review journals. He has 42 numbers of national and international publications to his credit. He has written three books, twelve chapters and edited one book. He is now continuing his research on biological control agents like *Chrysoperla zastrowi sillemi*, gut microbes of insects and also do research on queen rearing in *Apis cerena indica*.

Mr. Chandan Kumar Panigrahi was born on November 11, 1999 into a Brahmin family in Jeypore, Odisha. He graduated [B.Sc(Hons) in Agriculture] in 2021 from the Institute of Agricultural Sciences, FAS, S'O'A -DU , Bhubaneswar. He further pursued Master's [M.Sc.(Agri.) Entomology] at Naini Agricultural Institute, SHUATS - Prayagraj, demonstrating exceptional excellence and a meritorious academic record. Currently, Mr. C.K. Panigrahi is a Ph.D. (Agri.) Scholar at the Faculty of Agricultural Sciences, S'O'A -DU, Bhubaneswar, specializing in Agricultural Entomology. His impressive academic journey includes the publication of 10 Research papers, 10 Review papers in reputable National and International peer-reviewed journals, 2 Indian Design Patent, 45 book chapters, around 10 Agri-based technical articles, and 2 newspaper articles. He had partaken in an array of seminars, conferences, and training programmes, and for his diligent endeavours, he has been honoured with the Young Entomologist Award, Best Oral Presentation and the Young Research Scholar Award. He is likewise an ardent enthusiast of melodies and possesses a melodious voice of his own. He believes that music possess a healing power over his mental well-being. Additionally, Mr. Panigrahi is the author of 5 books and serves as a reviewer for various journals.

Preface

The book Pest Management in Crops and Stored Grains addresses one of the most critical challenges facing global food security—minimizing crop losses caused by insect pests, weeds, pathogens, and storage infestations while ensuring sustainability and environmental safety. Pests are responsible for significant yield reduction in cereals, pulses, oilseeds, fruits, vegetables, and cash crops, as well as heavy post-harvest losses in stored grains, threatening both farmer livelihoods and consumer nutrition. Traditional reliance on chemical pesticides has provided short-term control but has also led to the emergence of resistance, resurgence of secondary pests, environmental contamination, and food safety concerns. With rising consumer demand for residue-free produce, international trade regulations, and climate change intensifying pest dynamics, there is an urgent need for holistic, integrated strategies. This volume brings together recent advances in integrated pest management (IPM), biocontrol agents, host plant resistance, nanotechnology, pheromone and trap-based monitoring, and safe storage technologies to offer a comprehensive understanding of sustainable solutions. The book emphasizes ecological approaches that harmonize biological, cultural, mechanical, and chemical methods to reduce pest pressure while preserving beneficial organisms. Special focus is given to innovations in stored grain protection, hermetic storage structures, modified atmospheres, and eco-friendly protectants that minimize post-harvest losses without compromising grain quality. Each chapter is contributed by subject experts and provides critical insights into both theoretical frameworks and field-level applications, making it a valuable resource for researchers, academicians, students, extension professionals, policymakers, and practitioners in agriculture and allied sectors. By linking science with practice, this edited volume aims to serve as a reference point for promoting resilient crop production systems and safe storage practices that enhance food security, economic profitability, and environmental sustainability.

Editors

Table of Content

Chapter No.	Chapter Name	Page No.
1	**Introduction to Arthropod Pests and Their Economic Significance** *Karniel Dirchi*	1-17
2	**Scientific Classification and Bionomics of Key Crop Pests** *Rahul Jagannath Patil, Nandkumar Kallappa Kamble and Satyawan Patil*	18-42
3	**Pest Complexes and Management in Cereal and Pulse Crops** *Sushant Kumar*	43-65
4	**Pest Management in Vegetable Crops** *Priyanka Handique, Shruti Biradar and Vaishnavi Tathode*	66-83
5	**Insect Pests of Fruit and Plantation Crops** *Pramod S Sonawane, Rakesh B. Patil and Hiraman Burbude*	84-102
6	**Pest Management in Spices, Condiments, and Ornamental Plants** *S. Pushpatha, D. Nagaraju and B. Sravanthi*	103-117
7	**Structural Entomology and Urban Pest Management** *Sudhanshu Raikwar and Devina Seram*	118-137
8	**Post-Harvest Losses and Factors Affecting Stored Grain Quality** *Viresh Sadashiv Jeur, Shridhar Nivas Banne and Kalyani Ashok Jadhav*	138-155
9	**Rodents, Birds, and Microbial Threats in Grain Storage**	156-169

	Surendra Prasad, Surekha Kamlesh Kurankar and Priya Kashyap	
10	**Non-Insect Pests: Mites, Snails, and Slugs** *Shruti Biradar, Satappa Kharbade and Aishwarya Chavan*	**170-185**
11	**Concept and Application of Integrated Pest Management (IPM)** *Sanjeev Kumar, Surekha Kamlesh Kurankar and Priya Kashyap*	**186-206**
12	**Recent Advances: Insecticides, Biorational Pesticides, Drones, and AI** *Shruti Biradar, Satappa Kharbade and Vaishnavi Tathode*	**207-227**

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Chapter 1

Introduction to Arthropod Pests and Their Economic Significance

Karniel Dirchi

PhD Scholar, Rajiv Gandhi university, rono hills doimukh, Arunachal Pradesh.

Corresponding Author Email: Dirchikarniel1@gmail.com

A pest is any organism that interferes with human activities, especially those related to agriculture, food storage, forestry, and health. In agricultural contexts, a pest typically refers to an insect, mite, nematode, rodent, bird, or pathogen that causes damage to crops either by direct feeding or by acting as a vector for disease. Among these, arthropod pests, including insects and mites, are of major concern due to their widespread occurrence, high reproductive potential, and significant destructive capacity. These organisms reduce both the quantity and quality of crop yields, often resulting in considerable economic losses. The term "pest" is also dynamic; an organism may be classified as a pest only under certain environmental, economic, or crop-specific conditions.

A. Importance of Pest Management in Agriculture

Pest management plays a pivotal role in ensuring agricultural productivity, food security, and economic stability. Arthropod pests are responsible for significant pre- and post-harvest losses, with global estimates suggesting that they destroy approximately 18–20% of total crop production annually. In cereal crops like rice, wheat, and maize, pest-related yield losses can range between 15% to 25% under moderate infestation, and may reach up to 50% in severe outbreaks. Pests such as the brown planthopper (*Nilaparvata lugens*) in rice, the pod borer (*Helicoverpa armigera*) in pulses, and the fall armyworm (*Spodoptera frugiperda*) in maize are among the most damaging arthropods. Effective pest management not only safeguards yield but also preserves grain quality, minimizes economic losses to farmers, reduces pesticide dependency, and delays the development of pest resistance to control measures.

B. Scope and Objectives of Studying Arthropod Pests

Arthropod pests are essential for developing sustainable, ecologically sound pest control strategies. The study encompasses identification, taxonomy, biology, life cycles, host-pest interactions, modes of feeding, and ecological adaptations. The objectives include: (1) recognizing economically important arthropods and their characteristic damage symptoms; (2) pest behavior and population dynamics under various agro-climatic conditions; (3) determining economic threshold levels (ETLs)

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to inform timely control measures; and (4) developing integrated pest management (IPM) strategies that combine biological, cultural, mechanical, and chemical methods. The scope further extends to stored grain protection, as post-harvest losses due to pests such as *Sitophilus oryzae* (rice weevil) and *Tribolium castaneum* (red flour beetle) contribute to 5–10% grain loss during storage under traditional practices. The inclusion of arthropod pest management in academic curricula prepares students and professionals for informed decision-making in pest surveillance and control planning.

C. History on Pest Problems in Agriculture

Historical records indicate that pest problems have affected agriculture since the earliest periods of crop cultivation (Dark *et.al.,* 2001). Ancient civilizations documented insect outbreaks and devised rudimentary control methods. Chinese texts from around 300 BCE described the use of botanical insecticides and predator ants in citrus orchards. Egyptian hieroglyphs illustrate locust swarms destroying crops, while Roman agricultural texts mentioned techniques such as smoke fumigation and the use of sulfur to combat insect infestations. With the advent of large-scale agriculture during the industrial revolution, pest issues intensified, driven by monoculture practices and habitat disruption. Synthetic chemical pesticides gained popularity in the mid-20th century, beginning with DDT in the 1940s. Although initially successful, this approach led to unintended consequences such as pesticide resistance, resurgence of secondary pests, and ecological imbalance. By the late 20th century, these challenges led to the emergence of integrated pest management as a scientific and policy-driven framework aimed at long-term pest suppression with minimal environmental harm. Historical shifts in pest control highlight the ongoing evolution of agricultural pest management practices in response to ecological, technological, and economic changes.

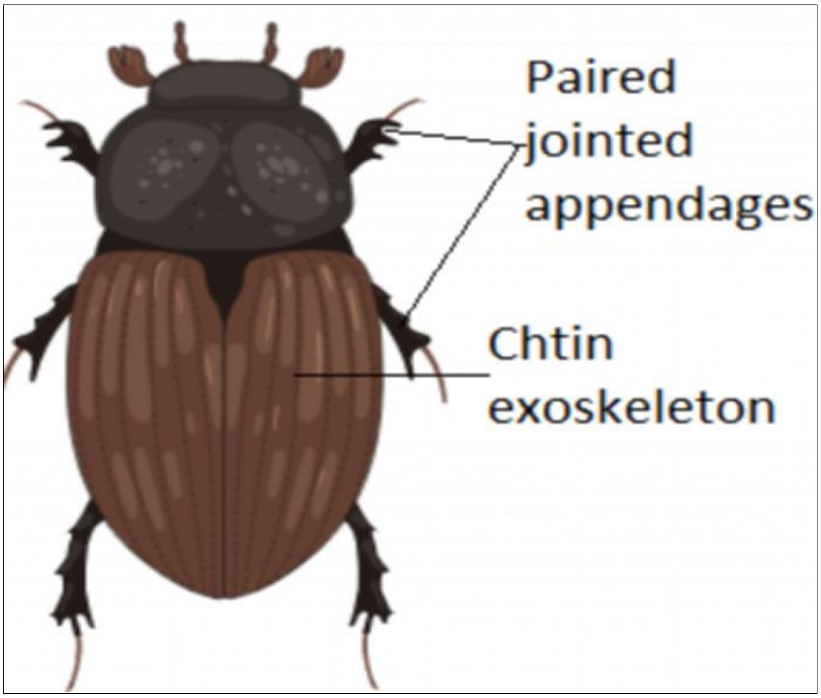
General Classification of Arthropod Pests

A. The Phylum Arthropoda

The phylum Arthropoda represents the largest and most diverse group in the animal kingdom, encompassing over one million described species, with estimates suggesting millions more remain undocumented. Arthropods are characterized by their segmented bodies, jointed appendages, and exoskeleton composed of chitin. These organisms are bilaterally symmetrical, possess an open circulatory system, and exhibit various forms of metamorphosis during their life cycles. The phylum includes several subgroups such as insects, arachnids, myriapods, and crustaceans. Arthropods are ecologically versatile and have colonized nearly every terrestrial and aquatic habitat. Their adaptability, high fecundity, and diverse feeding strategies have made certain species major agricultural and storage pests across different cropping systems.

B. Characteristics of Arthropod Pests

Arthropod pests display specific traits that enable them to become dominant in agricultural ecosystems. These characteristics include short generation times, high reproductive potential, mobility, and the ability to adapt quickly to environmental changes and pest control measures. Many pest species possess specialized mouthparts that allow them to feed on various plant tissues, including leaves, stems, roots, fruits, and seeds. Their feeding habits not only result in direct tissue damage but also facilitate the entry of plant pathogens and promote disease outbreaks. Some species exhibit cryptic habits, such as boring into plant tissues or living underground, which complicates detection and control. Others can overwinter or aestivate in soil or crop residues, surviving adverse conditions and reemerging in favorable seasons. Pests such as *Spodoptera litura*, *Helicoverpa armigera*, *Tetranychus urticae*, and *Sitophilus oryzae* exemplify the destructive potential of arthropods due to their adaptability and resilience.



C. Classification Based on:

1. Taxonomy

a. Insecta (Insects)

Insects form the largest class within Arthropoda and include most of the economically significant agricultural pests. They have a three-segmented bodyhead, thorax, and abdomenthree pairs of legs, compound eyes, and typically one or two pairs of wings. Insects such as aphids, whiteflies, thrips, beetles, caterpillars, and grasshoppers cause direct and indirect damage to crops. For example, *Nilaparvata lugens* affects rice yields by feeding on phloem sap and transmitting viral diseases, while *Leucinodes orbonalis* damages brinjal fruits internally, rendering them unmarketable.

b. Arachnida (Mites, Spiders)

Arachnids are characterized by two main body segments, four pairs of legs, and the absence of antennae and wings (Kennedy *et.al.,* 2021). Among arachnids, mites such as *Tetranychus urticae* (two-spotted spider mite) and Polyphagotarsonemus latus (broad mite) are common crop pests. They feed by piercing plant tissues and sucking out cell contents, leading to chlorosis, leaf curling, and reduced photosynthesis. Infestations are often favored by hot and dry conditions, leading to rapid population build-up on crops like cotton, chilli, and beans.

c. Crustacea (Occasional pests)

Crustaceans are mostly aquatic arthropods, but a few species like *Talitroides topitotum* and woodlice may infest damp agricultural environments or stored products under high humidity. While not major pests in most cropping systems, their presence in certain storage conditions can contribute to spoilage and contamination of food grains and other organic materials.

2. Mode of Life

a. Biting and chewing insects

These pests possess mandibulate mouthparts that allow them to chew and tear plant tissues. Common examples include caterpillars (larvae of moths and butterflies), beetles, and grasshoppers. Damage includes defoliation, fruit boring, and root feeding. *Spodoptera frugiperda* feeds voraciously on maize foliage, resulting in heavy defoliation and reduced photosynthetic activity.

b. Sucking pests

Sucking insects are equipped with stylet-like mouthparts designed for piercing plant surfaces and extracting sap. This group includes aphids, whiteflies, mealybugs, and leafhoppers. These pests not only reduce plant vigor but are also efficient vectors of viral and phytoplasma diseases. For example, *Bemisia tabaci* not only depletes nutrients from plants like cotton and tomato but also transmits over 100 plant viruses globally.

c. Boring insects

Boring pests are those that burrow into plant tissues, including stems, shoots, roots, and fruits. The internal feeding makes early detection difficult and control

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challenging. Notable examples are stem borers like *Scirpophaga incertulas* in rice and fruit borers like *Helicoverpa armigera* in tomato and cotton. Their damage typically leads to wilting, reduced fruit quality, and yield losses.

d. Soil-dwelling pests

Soil pests live and feed within the soil, attacking roots, germinating seeds, or underground stems. White grubs, termites, cutworms, and wireworms are prominent soil pests. These pests affect crops during the early growth stages, leading to poor crop stand and reduced yield. Termites, feed on root tissues and cause plant lodging, especially in sugarcane and groundnut.

3. Host Relationship

a. Monophagous

Monophagous pests are highly host-specific and feed on a single plant species or genus. This specialization may increase their efficiency in damaging the host crop. An example includes *Dacus cucurbitae*, which primarily attacks cucurbitaceous vegetables, causing severe fruit damage.

b. Oligophagous

Oligophagous pests have a narrow host range and feed on a few closely related plant species. The red cotton bug, *Dysdercuscingulatus*, infests cotton and other Malvaceae family members. These pests often exhibit host preference but can survive on alternative hosts under crop rotation practices.

c. Polyphagous

Polyphagous pests feed on a wide range of crops and are often more difficult to manage due to their adaptability. *Helicoverpa armigera* is a classic example, affecting more than 200 plant species including cotton, tomato, chickpea, and sunflower. Its wide host range enables year-round survival and frequent outbreaks.

4. Habitat

a. Field pests

Field pests infest crops during their growth in agricultural fields. Their activity is seasonal and closely related to crop phenology and climatic conditions. Examples include stem borers in cereals, leaf folders in rice, and jassids in cotton. These pests can cause localized or widespread epidemics depending on rainfall, temperature, and host availability.

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b. Stored grain pests

Stored grain pests infest harvested produce during storage and can lead to qualitative and quantitative losses. Key species include *Sitophilus oryzae* (rice weevil), *Tribolium castaneum* (red flour beetle), and *Rhyzoperthadominica* (lesser grain borer). These insects breed in storage bins, sacks, or godowns and can reduce grain weight, viability, and market value significantly. Under improper storage conditions, total losses may reach up to 30%.

c. Household pests

Certain arthropods may infest both agricultural storage and domestic spaces, feeding on food grains, dried fruits, and household items. Examples include *Lasioderma serricorne* (cigarette beetle) and *Trogoderma granarium* (khapra beetle), which are known to invade household pantries and traditional grain storage systems. Their presence results in contamination, foul odors, and degradation of stored products.

Types of Feeding by Arthropod Pests

A. Chewing Type

Chewing-type pests possess mandibulate mouthparts that are adapted for biting, cutting, and tearing plant tissues (Saikia *et.al.,* 2022). These mouthparts consist of strong mandibles and maxillae which operate in a horizontal plane, enabling the insect to consume large portions of leaf lamina, stems, or even entire seedlings. This mode of feeding causes extensive defoliation and structural damage to crops, particularly during the vegetative stages.

1. Mouthpart adaptation

The mandibles are robust and heavily sclerotized to perform mechanical breakdown of plant tissue. The labrum acts as an upper lip to help manipulate food, while the labium and maxillae assist in sensory perception and movement of the food bolus into the preoral cavity. The entire apparatus is well-suited for processing solid food, particularly fibrous plant material.

2. Examples: Caterpillars, Beetles

Caterpillars such as *Spodoptera litura* and *Helicoverpa armigera* consume large areas of foliage in crops like cotton, groundnut, tomato, and soybean. Their larval stages are the most destructive, often capable of skeletonizing leaves or boring into reproductive parts. Beetles like *Leptinotarsa decemlineata* (Colorado potato beetle) and *Callosobruchus chinensis* (pulse beetle) feed on leaves, roots, or seeds, depending on the species. Some species, such as blister beetles and flea beetles, are also vectors for plant pathogens.

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B. Sucking Type

Sucking pests possess piercing-sucking mouthparts that are adapted to extract liquid contents from plant tissues. These insects feed primarily on phloem or xylem sap, depriving the plant of nutrients and water, leading to physiological stress and in some cases systemic diseases.

1. Piercing and sucking mechanism

The mouthparts consist of a slender stylet housed within a grooved labium. The stylet penetrates the plant surface, navigates intercellular spaces, and reaches the vascular bundles. Saliva is injected to facilitate feeding and suppress plant defenses, followed by ingestion of plant sap through a food canal. Feeding punctures often go unnoticed until symptoms such as leaf curling, chlorosis, or stunted growth appear.

2. Examples: Aphids, Jassids, Whiteflies

Aphids like *Aphis gossypii* and *Myzus persicae* are major phloem feeders that cause direct sap loss and also transmit over 100 plant viruses, including those affecting cucurbits and solanaceous crops. Jassids (*Amrasca biguttula*) suck sap from cotton and okra, causing hopper burn symptoms, where leaf margins turn brown and curl inward. Whiteflies (*Bemisia tabaci*) feed on numerous vegetable and ornamental crops, leading to leaf yellowing, honeydew deposition, and secondary fungal infections such as sooty mold.

C. Boring Type

Boring pests create tunnels or galleries within plant tissues, feeding internally and often remaining hidden during most of their life stages. This makes early detection difficult and results in extensive internal damage before visible symptoms appear.

- *Stem borers, fruit borers*

Stem borers such as *Scirpophaga incertulas* (rice yellow stem borer) bore into the stem and disrupt nutrient transport, leading to dead hearts and whiteheads in rice plants. Fruit borers like *Leucinodes orbonalis* in brinjal and *Helicoverpa armigera* in tomato and cotton feed within the fruiting structures, causing premature fruit drop, internal rotting, and loss of marketability. The concealed feeding nature of these pests often necessitates specialized management tactics such as pheromone traps or systemic insecticides.

D. Mining and Scraping Type

Leaf miners feed between the upper and lower epidermal layers of leaves, creating serpentine or blotch-shaped mines. This type of damage reduces photosynthetic activity and weakens the plant. Typical leaf miners include species from the genera Liriomyza and Phyllocnistis. Scraping feeders, such as thrips, lacerate the epidermis

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of leaves or flowers and feed on the exuding sap. Their activity results in silvering, curling, and deformation of leaves, as seen with Thrips tabaci in onion and Frankliniella occidentalis in various vegetables and ornamentals.

E. Gall Formation

Certain arthropod pests induce abnormal plant growth in the form of galls, which are localized swellings or tumor-like structures that serve as both habitat and food source for the developing immature stages of the pest. Gall formation is caused by the injection of chemical secretions or mechanical irritation during feeding or oviposition. The mango gall midge (*Procontarinia matteiana*) and eriophyid mites (*Aceria* spp.) cause gall formation in mango leaves and buds, leading to reduced fruit set and deformities. Galls disrupt normal plant physiology and reduce overall plant vigor.

F. Other Specialized Feeding Types

Some arthropods display highly specialized feeding mechanisms. Mites such as Polyphagotarsonemus latus feed by rupturing plant cells and sucking out the contents, causing leaf curling and chlorosis in crops like chilli and beans. Thrips, though classified under scraping feeders, often display a unique feeding style that combines cell rupture and suction. Mealybugs (*Phenacoccus solenopsis*) and scale insects secrete waxy coatings and feed continuously on plant sap, often forming colonies on stems, leaves, or roots. Their feeding is associated with excretion of honeydew, which promotes fungal growth and impairs plant respiration.

Damage Symptoms Caused by Arthropod Pests

A. Direct Damage

Arthropod pests inflict direct damage to crops by physically feeding on plant tissues, resulting in structural injuries and functional impairment. One of the most visible forms of direct damage is defoliation, where chewing insects such as caterpillars remove significant portions of the leaf area. This reduction in foliage disrupts photosynthesis, leading to stunted growth, poor yield formation, and reduced crop quality. Heavy infestations by pests like *Spodoptera litura* and *Achaea janata* can completely skeletonize leaves in soybean, cotton, groundnut, and castor, resulting in yield losses that may exceed 30% under uncontrolled conditions.

1. Defoliation

Defoliation primarily occurs due to feeding by larvae of Lepidoptera and certain Coleoptera. Crops at the vegetative stage are especially vulnerable, as leaf area index (LAI) is critical for light interception and biomass accumulation. When more than 30–40% of the foliage is consumed, grain formation and fruit setting are severely compromised. Late-season defoliation may also affect crop maturity and disrupt harvest timelines.

2. Boring into stems, fruits, and roots

Boring insects feed internally within plant parts, leading to hidden yet extensive damage (Sreedevi *et.al.,* 2022). Stem borers like *Scirpophaga incertulas* in rice cause dead hearts at the tillering stage and whiteheads during panicle emergence, which represent sterile panicles with no grain filling. Fruit borers such as *Helicoverpa armigera* in tomato and cotton drill into developing fruits and bolls, rendering them unfit for consumption or processing. Root borers like white grubs damage the root system of sugarcane and groundnut, disrupting water and nutrient uptake and often causing plant lodging and death. The damage caused by borers is difficult to reverse due to its internal nature and the reduced efficacy of contact insecticides.

3. Sucking sap from plant tissues

Sucking pests such as aphids, whiteflies, jassids, and mealybugs pierce plant tissues and extract sap, causing dehydration, chlorosis, curling of leaves, and overall wilting. Their feeding interferes with plant physiology, including the balance of growth hormones, leading to abnormal development. In crops like cotton, sap-sucking pests can reduce lint quality, induce flower shedding, and cause boll drop. The feeding activity of whiteflies and aphids also leads to honeydew excretion, which supports the growth of sooty mold, blocking sunlight and reducing photosynthetic efficiency.

B. Indirect Damage

Arthropod pests are also responsible for significant indirect damage that results not only from their feeding but also from their role in facilitating other biological stresses. One of the most critical forms of indirect damage is the transmission of plant pathogens. Many sucking pests act as vectors for viruses, phytoplasmas, and bacteria, leading to systemic infections in crops.

1. Transmission of plant pathogens

Aphids, whiteflies, and leafhoppers are known to transmit over 200 plant viruses worldwide. For example, *Bemisia tabaci* is a major vector of Tomato Leaf Curl Virus (ToLCV), which can reduce tomato yield by up to 90% in severely infected fields. Leafhoppers such as *Nephotettix virescens* transmit rice tungro virus, while aphids like *Myzus persicae* are responsible for the spread of Potato Virus Y (PVY) and Cucumber Mosaic Virus (CMV). These diseases spread rapidly under favorable environmental conditions and are often more damaging than the pest’s direct feeding.

2. Introduction of secondary infections

Feeding injuries serve as entry points for opportunistic fungal and bacterial pathogens. Stem boring by *Sesamia inferens* in sugarcane creates wounds that are later colonized by red rot fungi (*Colletotrichum falcatum*), leading to rotting of internal tissues. Mealybug infestations on fruits like guava or pomegranate are frequently followed by sooty mold development due to honeydew excretion, making the produce unfit for the fresh market. The combined impact of pest feeding and subsequent microbial infection can be far more severe than either alone.

3. Loss of photosynthetic area

When pests damage leaf surfaces through chewing, mining, or scraping, the chlorophyll-bearing tissues are destroyed, reducing the plant's capacity for photosynthesis. Leaf miners such as *Liriomyza trifolii* create serpentine mines that disrupt chloroplast-containing mesophyll cells. Thrips feeding leads to silvering or bronzing of leaves, as seen in chilli, onion, and cabbage, reducing the photosynthetic potential and weakening the plant. In many horticultural crops, such reductions not only lower yields but also affect visual quality, making the produce less acceptable in fresh markets.

C. Examples with Crops

1. Paddy: Stem borer

In paddy, the rice stem borer (*Scirpophaga incertulas*) causes two distinct types of symptoms. At the vegetative stage, dead hearts occur when the growing shoot is destroyed, resulting in yellowing and drying of the central tiller. At the reproductive stage, the same pest causes whiteheads, a condition where the panicle emerges but remains empty due to the disruption of nutrient flow. Yield losses from stem borer infestations can range from 10% to 60% depending on the stage of attack and severity.

2. Cotton: Bollworms

In cotton, bollworms including *Helicoverpa armigera* and *Earias vittella* bore into developing bolls, disrupting fiber formation and leading to flower drop and reduced boll set. Damage is most severe during the reproductive phase and can result in economic losses exceeding 50% if not controlled promptly. Bollworms also expose internal tissues to secondary microbial attacks, further degrading cotton quality.

3. Wheat: Aphids

In wheat, aphids such as *Rhopalosiphummaidis* and *Schizaphisgraminum* colonize leaves and earheads, sucking sap and causing leaf curling, yellowing, and poor grain filling. They also secrete honeydew, encouraging the growth of black sooty mold.

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High aphid populations during the grain-filling stage can reduce yield by 15–25% and lower seed viability for the next season.

4. Stored Grains: Rice weevil

Stored grains are frequently attacked by pests such as the rice weevil (*Sitophilus oryzae*), which bores into the grain kernel and feeds on the endosperm. The damage causes both quantitative loss through weight reduction and qualitative loss due to grain dusting, contamination, and reduction in market value. Under poor storage conditions, infestation levels can lead to losses exceeding 30% of the stored produce within a few months.The symptoms caused by arthropod pests, whether direct or indirect, represent critical indicators for field monitoring, pest diagnosis, and management decisions. These signs and associating them with specific pests allows for timely interventions and reduces the potential for economic and food security losses.

Economic Threshold Level (ETL)

A. Definition and Concept of ETL

The Economic Threshold Level (ETL) is a critical concept in pest management that serves as a decision-making tool for determining the appropriate timing of pest control measures. ETL is defined as the pest population density at which control measures should be initiated to prevent an increasing pest population from reaching the Economic Injury Level (EIL). The EIL represents the lowest pest density that will cause economic damage. ETL always lies below the EIL and serves as a preventive point to initiate control actions. By relying on ETL, farmers and agricultural professionals can minimize unnecessary pesticide applications, reduce production costs, delay resistance development, and maintain ecological balance. The concept of ETL is integral to integrated pest management (IPM) strategies, ensuring that pest control efforts are economically justified and environmentally sustainable.

B. Components of ETL

ETL is not a fixed value but is influenced by several dynamic variables related to pest biology, crop value, and agro-ecological conditions. Among these, pest population density is the primary driver in determining ETL. The number of pests per unit area, per plant, or per leaf is measured through field scouting or trapping, and when this density approaches the threshold, control measures must be taken. For example, the ETL for *Helicoverpa armigera* in chickpea is 1–2 larvae per meter row length or 5–10% pod damage.

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1. Pest population density

Pest density is usually monitored through direct counts, light traps, pheromone traps, or sweep nets. It helps estimate the potential damage a pest can cause if no action is taken. The accuracy and frequency of monitoring are essential for calculating effective ETLs and initiating timely interventions.

2. Crop stage

The vulnerability of crops to pests varies with growth stages. The vegetative phase of maize is more susceptible to fall armyworm, while rice is more sensitive to stem borers during tillering and panicle initiation stages. ETLs are adjusted based on crop phenology to prevent irreversible yield losses during critical growth periods.

3. Crop value and input cost

High-value crops such as cotton, tomato, and chilli generally have lower ETLs due to the potential financial loss per unit damage. When the market price of a crop is high, even a low pest density can cause significant economic damage. Input costs such as fertilizers, labor, and irrigation also influence the threshold; expensive inputs increase the cost of production, thereby lowering the acceptable pest tolerance level.

C. Economic Injury Level (EIL) vs. ETL

The Economic Injury Level is the point at which the economic loss caused by pest damage exceeds the cost of control measures (Higley *et.al.,* 1986). ETL, being a preventive threshold, is set below the EIL to ensure that pest populations are managed before reaching damaging levels. While EIL represents the economic limit of tolerance, ETL provides a practical guideline for when to act. For example, if the EIL for whitefly in cotton is 10 adults per leaf, the ETL might be fixed at 6–8 adults to allow enough lead time for effective control. This margin helps avoid delayed action, which could lead to pest outbreaks and yield loss.

D. Factors Influencing ETL

Multiple variables influence the setting and effectiveness of ETL values. These include pest species behavior and reproductive potential, prevailing climatic conditions, and specific crop characteristics.

1. Pest species

Different pests have varying feeding habits, life cycles, and damage potential. Polyphagous pests such as *Helicoverpa armigera* can attack a wide range of crops and have a high reproductive rate, which necessitates a lower ETL. Pests with slower population growth may have higher threshold values, as their damage can be managed with fewer interventions.

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2. Climatic conditions

Temperature, humidity, and rainfall play a significant role in pest population dynamics. Warm, humid conditions favor the rapid multiplication of pests like aphids, whiteflies, and mites. During dry spells, sucking pests tend to proliferate, often breaching ETL quickly. Seasonal shifts also influence pest emergence patterns, requiring ETL values to be periodically adjusted according to climatic trends.

3. Crop type and growth stage

Certain crops are naturally more resilient or tolerant to pest attacks due to their morphological or biochemical properties. Sorghum can withstand some level of stem borer infestation without major yield loss due to its tillering capacity. Crops in early growth stages are generally more vulnerable, prompting lower ETLs. Mature plants may withstand some pest load without economic consequences, allowing for a higher ETL under certain circumstances.

E. Importance of ETL in Integrated Pest Management (IPM)

ETL serves as the cornerstone of IPM by promoting judicious use of chemical control and encouraging alternative management strategies. By initiating control measures only when pest populations reach the threshold, ETL prevents unnecessary pesticide applications, conserves natural enemies, and delays the development of resistance. It also reduces the environmental footprint of pest control operations and contributes to sustainable crop production. In IPM programs, ETLs are often used alongside cultural, biological, and mechanical control methods. Scouting protocols, economic assessments, and predictive modeling are integrated with ETL to ensure timely and effective pest management decisions.

F. Examples of ETLs for Key Pests

The ETL for *Nilaparvata lugens* (brown planthopper) in rice is typically 10 insects per hill during the early vegetative stage or 20 insects per hill at the booting stage. For *Spodoptera frugiperda* (fall armyworm) in maize, the ETL is generally one larva per plant or 5% of plants showing whorl damage. In cotton, the ETL for *Bemisia tabaci* (whitefly) is around 5–6 adults per leaf or the presence of honeydew on 50% of plants. For *Rhyzoperthadominica* in stored grains, the ETL is usually considered as one live adult per kilogram of grain sample. These threshold values are periodically updated based on pest surveillance data, crop value, and agro-climatic changes. Economic Threshold Levels provide a rational, evidence-based approach to managing pest populations. They balance the need to protect crops with the goal of preserving agroecosystem health and economic viability. By relying on ETL, pest management transitions from reactive to proactive, reducing over-

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dependence on chemical control and laying the foundation for sustainable agricultural practices.

Pest-Induced Crop Losses

A. Types of Losses

Arthropod pests cause significant losses to agricultural productivity by affecting both the quantity and quality of the produce. These pest-induced losses vary depending on the type of crop, pest species, infestation stage, and environmental conditions. The damage can occur at any stage of crop growthfrom seedling emergence to post-harvest storageand is categorized into quantitative and qualitative losses.

1. Quantitative Losses (yield reduction)

Quantitative losses refer to the measurable reduction in crop yield due to direct feeding or pest activity. This may include damage to vegetative parts such as leaves and stems, reproductive parts like flowers and fruits, or underground structures such as roots and tubers. Infestation by *Spodoptera frugiperda* in maize during the early vegetative stage can reduce grain yield by 20% to 40%, while *Helicoverpa armigera* in pulses like chickpea and pigeon pea can lead to yield losses of 30% or more. Stem borers in rice and sugarcane can cause significant damage, with rice yields declining by 15% to 60% depending on the severity and timing of infestation. The cumulative impact of multiple pests across seasons can lead to reduced farm income, increased input costs, and food insecurity.

2. Qualitative Losses (grain quality, market value)

Qualitative losses involve deterioration in the quality or market value of agricultural produce. Such losses are common in fruit, vegetable, and grain crops where even minor blemishes or internal damage can make the produce unfit for sale or processing. In fruits like tomato and brinjal, fruit borers cause internal damage that renders the fruit unmarketable, even if the yield is not significantly reduced. In grains, infestation by storage pests such as *Sitophilus oryzae* and *Tribolium castaneum* lowers seed viability, nutritional value, and germination potential. Discoloration, contamination with insect parts, and foul odors further reduce the market acceptance of stored grains. In cotton, bollworm damage can reduce fiber strength and affect ginning efficiency, leading to a decline in lint quality and price in the textile market. Even minor aesthetic damage in export-oriented crops like chilli, grapes, and mango can result in significant financial losses due to rejection in international markets.

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B. Factors Affecting Loss Severity

The extent of crop loss caused by pests is influenced by several biological, agronomic, and environmental factors. The relationship between pest behavior and crop vulnerability is critical in determining the severity of damage.

1. Pest population and duration

The size of the pest population and the duration of infestation are key variables in determining crop loss. High pest density over an extended period leads to sustained feeding pressure, often overwhelming the plant's ability to recover. For example, continuous infestation of aphids over several weeks can reduce wheat yield by more than 25%, especially during the grain-filling stage. Pests with multiple overlapping generations, such as whiteflies and mites, tend to maintain high population levels throughout the cropping period, compounding the damage.

2. Crop stage and type

Crops are more susceptible to pest damage during certain growth stages. Reproductive stages such as flowering and grain or fruit development are particularly vulnerable because damage at this time has a direct impact on final yield. For example, *Leucinodes orbonalis* attacking brinjal during fruiting can result in 50% to 70% fruit loss. Similarly, the late vegetative to early reproductive phase in cotton is highly sensitive to bollworm attack. Crop architecture and physiological traits also influence susceptibility. Dense canopy structures may favor pest buildup, while certain leaf textures or chemical profiles may deter or attract specific pests.

3. Pest-crop-environment interactions

Environmental conditions such as temperature, humidity, and rainfall patterns significantly influence pest dynamics and crop susceptibility. Warm and humid climates promote the multiplication of sucking pests and mites, often leading to outbreaks. Water stress or nutrient deficiencies can weaken plant defenses, making crops more prone to pest attacks. Conversely, well-managed agroecosystems with crop rotation and intercropping may disrupt pest cycles and reduce infestation pressure. Natural enemies such as parasitoids and predators also play a role in modulating pest populations, and their absence due to indiscriminate pesticide use can lead to secondary pest outbreaks and higher losses.

C. Estimation and Assessment Methods

Quantifying pest-induced crop losses is essential for planning pest management strategies and assessing the economic impact on farming systems (Soliman *et.al.,* 2015). Loss estimation involves both field-based observation and controlled experiments under research conditions.

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1. Field surveys

Field surveys are conducted during various crop growth stages to monitor pest populations and assess the extent of damage. These surveys use standard sampling techniques such as quadrat sampling, sweep net collection, and visual scoring of damage symptoms. Data collected from multiple fields are used to estimate average pest incidence and yield loss percentages. In rice, damage scoring for stem borers and leaf folders is often done using a 0–9 scale, correlating visual symptoms to estimated yield impact.

2. Controlled experiments

Controlled experiments are carried out under research station conditions where variables such as pest infestation level, crop variety, and environmental factors are systematically manipulated (Tooker *et.al.,* 2012). These experiments provide precise data on yield reduction per unit pest density and help in developing Economic Threshold Levels (ETLs) and predictive models. For example, studies on *Helicoverpa armigera* in chickpea have demonstrated yield loss increments of 5% for every additional larva per meter row length under untreated conditions. Experimental data are also used to evaluate the effectiveness of control measures and to refine integrated pest management protocols.

D. Case Studies

Historical case studies illustrate the real-world impact of pest outbreaks on crop production and economics.

1. Cotton pest outbreaks

Cotton has experienced repeated pest outbreaks involving bollworms, whiteflies, and jassids. One of the most notable examples includes the outbreak of *Helicoverpa armigera* in cotton fields, which led to yield losses of up to 70% in some regions during the mid-1990s. This period also saw a surge in pesticide use, resulting in pest resistance, resurgence of secondary pests, and ecological imbalance. The introduction of Bt cotton later mitigated bollworm-related losses, although new pest challenges such as pink bollworm and sucking pests have since emerged. These outbreaks underscore the need for sustainable pest monitoring and management practices.

2.Stored grain pest infestations

Post-harvest losses due to stored grain pests are often underestimated but significantly impact food availability and quality. Under traditional storage systems, grain weight loss due to pests such as *Sitophilus oryzae*, *Rhyzoperthadominica*, and *Trogoderma granarium* can exceed 20% within six months. Infestation leads to caking, moisture accumulation, and heating, which further degrade the grain quality.

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Loss of germination potential in seed stocks affects the next planting season and increases reliance on external seed sources. The economic burden includes not just the cost of grain lost, but also expenses on fumigation, pest-proof storage structures, and quality control measures. Pest-induced crop losses represent a significant constraint to agricultural productivity and profitability. Recognizing the types, causes, and impacts of such losses is essential for designing effective pest surveillance, prevention, and control strategies. Through regular monitoring, scientific estimation, and case-based learning, it becomes possible to minimize these losses and enhance the resilience of cropping systems against pest threats.

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Chapter 2

Scientific Classification and Bionomics of Key Crop Pests

Rahul Jagannath Patil*[1], Nandkumar Kallappa Kamble[2] and Satyawan Patil[3]

[1]*Assistant Professor, Department of Zoology, Balwant College, Vita, Dist. Sangli (Maharashtra) https://orcid.org/0000-0001-8642-2834*

[2]*Assistant Professor, Department: Department of Zoology, Dr. Patangrao Kadam Mahavidyalaya, Ramanandnagar (Burli)*

[3]*Associate Professor, Department of Zoology, ACS College, Palus, Affiliated to Shivaji University, Kolhapur*

***Corresponding Author Email:** *rahulspiderfauna1@gmail.com*

Introduction:

The study of insect pests is an essential component of agricultural science due to their direct and indirect impact on crop health and yield. Entomological research enables a deeper of pest biology, behavior, and ecological relationships, which is critical for designing effective management strategies. These insect pests affect every stage of crop growth, from germination to harvest, making them one of the leading causes of yield loss across various agroecosystems. Modern agriculture demands sustainable approaches to pest management, which can only be achieved through comprehensive knowledge of pest diversity, life cycles, host preferences, and their interactions within the crop ecosystem.

A. Pest impact on crop production and economy

Crop losses attributed to insect pests account for approximately 15–25% of total agricultural output globally (Sharma *et.al.,* 2017). Insect pests reduce both the quality and quantity of produce, and in many cases, lead to complete crop failure. For example, *Helicoverpa armigera* is reported to cause losses exceeding USD 2 billion annually across various crops such as cotton, chickpea, tomato, and pigeon pea. Similarly, the brown planthopper (*Nilaparvata lugens*) is a major pest of rice, capable of causing hopper burn and transmitting viral diseases, leading to significant economic losses. Pest outbreaks also increase production costs due to the reliance on chemical control measures, which can further lead to pesticide resistance and environmental contamination. As a result, the economic burden caused by insect pests extends beyond yield reduction to include additional input costs and food security challenges.

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B. Definitions

1. Pest

A pest is defined as any organism that causes economic damage to crops, stored products, livestock, or humans by feeding on, competing with, or transmitting pathogens to the host. In the context of agriculture, insect pests are organisms belonging to the class Insecta that damage cultivated plants and reduce their economic value. The threshold at which a pest becomes economically significant is known as the Economic Injury Level (EIL), and the level at which control measures are initiated is termed the Economic Threshold Level (ETL).

2. Bionomics

Bionomics refers to the study of the mode of life of organisms, particularly their behavior, life history traits, ecological interactions, and environmental requirements. In the case of insect pests, bionomics includes the investigation of their life cycle, feeding habits, reproduction, seasonal activities, dispersal patterns, and survival strategies under varying environmental conditions. The bionomics of pests is crucial for predicting outbreaks, designing control measures, and minimizing pest-induced crop losses.

3. Scientific classification

Scientific classification, or taxonomy, is the systematic arrangement of organisms into hierarchical categories based on shared characteristics and evolutionary relationships. Insects are classified under the phylum Arthropoda, and their classification includes levels such as class, order, family, genus, and species. This classification allows for the accurate identification of pests, facilitates communication among researchers and practitioners, and helps in understanding the biology and ecology of pest species. For example, the cotton whitefly is classified as *Bemisia tabaci* (Order: Hemiptera, Family: Aleyrodidae), and its identification through scientific classification is vital for implementing specific control measures and understanding its resistance patterns.

Principles of Scientific Classification of Insects

A. Taxonomic hierarchy

The scientific classification of insects follows a hierarchical system that organizes living organisms based on shared morphological, physiological, and genetic characteristics. This system, universally accepted by biologists and entomologists, enables precise identification and understanding of insect diversity. The taxonomic hierarchy begins at the broadest level with the kingdom, which in the case of insects is Animalia, encompassing all multicellular organisms that are heterotrophic and capable of locomotion at some stage of life. Within this kingdom, insects fall under the phylum Arthropoda, characterized by jointed appendages, segmented bodies, and an exoskeleton composed of chitin. Arthropods are the most diverse phylum, containing over one million described species, with insects accounting for the largest portion.

Within Arthropoda, the class Insecta includes organisms with three distinct body regions (head, thorax, abdomen), three pairs of legs, compound eyes, and usually two pairs of wings. The class Insecta comprises more than 900,000 known species, playing various ecological roles ranging from pollinators to decomposers and, significantly, as pests of crops. Insects are then categorized into orders based on features such as wing structure, type of metamorphosis, and mouthparts. Major pest-related orders include Lepidoptera (moths and butterflies), Coleoptera (beetles), Hemiptera (bugs and aphids), Diptera (flies), and Orthoptera (grasshoppers and locusts). Each order is divided into families, grouping species with even closer morphological and behavioral similarities. Within Lepidoptera, the family Noctuidae includes many significant crop pests such as *Helicoverpa armigera* and *Spodoptera litura*. At a more specific level, organisms are identified by their genus and species, collectively referred to as the binomial nomenclature. The genus groups species with close genetic and evolutionary relationships, while the species denotes the individual organism type capable of interbreeding. For example, the fall armyworm is classified as *Spodoptera frugiperda*, where Spodoptera is the genus and frugiperda the species. This binomial system is critical for accurately referencing pest organisms and differentiating between morphologically similar species with varying pest statuses or behaviors.

B. Importance of classification in pest management

Accurate classification is essential for the effective management of insect pests in agriculture. Scientific identification ensures that pest control strategies are specifically targeted, avoiding unnecessary or ineffective treatments (Arif *et.al.,* 2017). Misidentification can result in inappropriate pesticide application, leading to resistance development, non-target effects, and economic loss. Whiteflies such as *Bemisia tabaci* and *Trialeurodes vaporariorum* differ in their pesticide susceptibility and virus transmission ability, necessitating species-level identification for proper control. Classification also aids in understanding the evolutionary relationships among pests, which can reveal patterns in behavior, physiology, and resistance mechanisms. This knowledge forms the foundation for integrated pest management (IPM) programs, which rely on accurate pest recognition to deploy biological controls, cultural practices, and chemical methods judiciously. Classification also plays a role in quarantine regulations and international trade, as accurate identification is required for the enforcement of phytosanitary measures to prevent the spread of invasive pest species.

C. Nomenclature rules (ICZN basics)

The binomial naming system is governed by the International Code of Zoological Nomenclature (ICZN), which provides rules for naming animal species to ensure consistency, universality, and stability in scientific communication. According to ICZN guidelines, the scientific name of an insect consists of two parts: the genus name, which is capitalized, and the species name, which is written in lowercase. Both parts are italicized or underlined when handwritten. For example, the correct format is *Helicoverpa armigera*. When citing an insect species for the first time, the author who first described the species and the year of description may also be included in parentheses, such as *Spodoptera litura* (Fabricius, 1775).

The ICZN rules specify that names must be unique, based on Latin or Latinized words, and must conform to grammatical standards. Priority is given to the earliest validly published name, a principle known as the Law of Priority. The naming of new species must be accompanied by a proper description and type specimen designation. Names may be revised if they are found to be incorrectly assigned, but changes are governed by strict protocols to avoid confusion. The consistent application of these nomenclature rules ensures clear communication among entomologists, researchers, and agricultural professionals globally, allowing for accurate identification, record-keeping, and data exchange on pest species.

General Bionomics of Insect Pests

A. Life cycle patterns

The life cycle of insect pests plays a crucial role in determining the timing and intensity of infestation on crops. Insects exhibit two main patterns of development: complete metamorphosis and incomplete metamorphosis. In complete metamorphosis, the insect undergoes four distinct developmental stages: egg, larva, pupa, and adult. Each stage differs morphologically and functionally. Larval stages are typically voracious feeders and cause the majority of damage to crops. Examples include pests like *Helicoverpa armigera* (cotton bollworm), *Spodoptera litura* (tobacco caterpillar), and *Plutella xylostella* (diamondback moth). The pupal stage is non-feeding and functions as a transitional phase during which the organism transforms into an adult. This form of development allows the immature and mature stages to occupy different ecological niches, reducing intraspecific competition. Incomplete metamorphosis involves three life stages: egg, nymph, and adult. Nymphs resemble adults in general appearance but lack fully developed wings and reproductive structures. They feed on the same host plants as adults and usually inhabit similar environments. Pests such as *Nilaparvata lugens* (brown planthopper), *Aphis gossypii* (cotton aphid), and *Locusta migratoria* (locust) follow this pattern. Since the immature and mature stages share the same resources, the damage inflicted on crops is continuous and accumulative throughout their lifecycle.

B. Reproductive strategies

Insect pests employ various reproductive strategies that enhance their capacity to colonize and damage crops rapidly. Many pests exhibit high fecundity, producing hundreds to thousands of eggs in a single generation. Female *Helicoverpa armigera* moths can lay up to 1,000 eggs during their lifespan. The short generation time and rapid development enable certain species to produce multiple overlapping generations within a cropping season. Parthenogenesis, or reproduction without fertilization, is another reproductive mechanism seen in pests such as *Aphis craccivora*, enabling quick population buildup in the absence of males. Some insects, including mealybugs and scales, exhibit viviparity, where eggs hatch inside the female's body and live young are born directly, accelerating establishment on host plants.

C. Seasonal behavior and generations

The seasonal activity of insect pests is strongly influenced by climatic conditions such as temperature, humidity, and photoperiod. Pests demonstrate distinct patterns of emergence, infestation, and reproduction aligned with the growth stages of their host crops. For example, *Chilo partellus* (maize stem borer) shows peak activity during the vegetative and early reproductive stages of maize, leading to maximum yield loss during those critical periods. Multivoltinism, or the ability to complete several generations per year, is a common trait among pests like *Spodoptera frugiperda* (fall armyworm), which can produce 6–8 generations annually under favorable conditions. This capacity contributes significantly to the difficulty of managing such pests across cropping seasons. Univoltine pests complete only one generation annually but may align their life cycles precisely with specific crop stages, causing damage at key developmental phases.

D. Survival mechanisms

Insect pests have evolved several strategies to survive adverse environmental conditions and ensure continuity across seasons.

1. Diapause

Diapause is a state of arrested development that allows insects to endure periods of environmental stress, such as extreme cold or drought. It is a hormonally controlled process triggered by external cues like decreasing day length or temperature. Insects such as *Sesamia inferens* (pink stem borer) enter larval diapause in the soil during the off-season, resuming activity when conditions become favorable for crop growth.

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2. Migration

Migration is a long-distance movement of pest populations from one region to another in search of suitable climatic and host conditions (Zeng *et.al.,* 2020). Species like *Spodoptera frugiperda* and *Nilaparvata lugens* exhibit migratory behavior, enabling them to invade large crop areas rapidly. These migrations are often seasonal and are influenced by wind patterns, crop availability, and environmental suitability.

3. Shelter-seeking behavior

Some pests adopt shelter-seeking habits to avoid unfavorable conditions or predation. *Scirpophaga incertulas* (yellow stem borer) larvae bore into rice stems, creating a protected niche for feeding and development. Similarly, *Leucinodes orbonalis* (brinjal shoot and fruit borer) larvae reside inside the fruit and shoots, making chemical control difficult. Such behaviors not only aid in pest survival but also complicate management practices by reducing pesticide exposure.

E. Pest-host interaction dynamics

The interaction between pests and their host plants is central to understanding pest biology and devising effective control strategies. Insect pests exhibit varying degrees of host specificity. Monophagous pests like *Pectinophoragossypiella* (pink bollworm) feed exclusively on cotton, while polyphagous pests such as *Helicoverpa armigera* and *Spodoptera litura* attack a wide range of crops including pulses, oilseeds, and vegetables. Host plant factors such as nutritional content, physical barriers (e.g., trichomes), and chemical composition influence pest preference and performance. Some pests exhibit selective feeding on specific plant parts*Brevicoryne brassicae* (cabbage aphid) targets young leaves and inflorescences, while *Callosobruchus chinensis* (pulse beetle) infests stored pulses. Understanding these dynamics is crucial for selecting resistant varieties, timing of interventions, and deploying targeted control measures. Host plant resistance, a component of integrated pest management, relies heavily on knowledge of pest-host interaction mechanisms including feeding behavior, oviposition preference, and physiological adaptation of pests to plant defenses.

Scientific Classification and Bionomics of Major Crop Pests

A. Pests of Cereals

1. Rice

a. Rice stem borer – Scirpophaga incertulas (Lepidoptera: Crambidae)

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Rice is a staple cereal crop affected by several destructive insect pests. One of the most damaging is the rice stem borer, *Scirpophaga incertulas*, classified under the order Lepidoptera and family Crambidae. Its host range is primarily confined to rice. This pest is distributed widely across tropical and subtropical regions of Asia and Southeast Asia. Females lay eggs on the leaf sheath, and upon hatching, larvae bore into the stem. The life cycle completes in about 30–50 days depending on climatic conditions. The bionomics includes five to six larval instars, a pupation stage within the stem, and adults that emerge during the night. Damage symptoms include dead hearts during vegetative growth and whiteheads during the reproductive phase.

b. Rice leaf folder – Cnaphalocrocis medinalis

Another common rice pest is the rice leaf folder, *Cnaphalocrocis medinalis*, belonging to the order Lepidoptera and family Crambidae. This pest feeds on rice leaves by folding them longitudinally and scraping the green matter, reducing photosynthetic area. The host preference is limited to rice and other grass species. The insect undergoes complete metamorphosis, with the larval stage responsible for feeding. The life cycle spans approximately 25–30 days under favorable conditions.

c. Rice hispa – Dicladispa armigera

The rice hispa, *Dicladispa armigera*, a beetle from the order Coleoptera and family Chrysomelidae, causes significant damage by scraping the upper leaf surface. Adult beetles and larvae both feed on rice leaves, leaving parallel white streaks. This pest thrives in warm and humid regions, especially during the monsoon. Its life cycle includes egg laying on leaf surfaces, followed by larval mining inside leaves, pupation within the leaf tissue, and emergence of metallic blue adult beetles in about 20–25 days.

Table: major and minor pests of Rice with their scientific names and taxonomic classification

S. No.	Common Name	Scientific Name	Family	Order	Category
1	Thrips	*Stenchaetothripsbiformis*	Thripidae	Thysanoptera	Major Pest
2	Green leafhopper	*Nephotettix virescens*, *N. nigropictus*, *N. cincticeps*	Cicadellidae	Hemiptera	Major Pest
3	Brown plant	*Nilaparvata lugens*	Delphacidae	Hemiptera	Major Pest

	hopper				
4	White backed plant hopper	*Sogatellafurcifera*	Delphacidae	Hemiptera	Major Pest
5	Rice earhead bug	*Leptocorisa acuta*	Alydidae	Hemiptera	Major Pest
6	Mealy bug	*Brevenniarehi*	Pseudococcidae	Hemiptera	Major Pest
7	Rice black bug	*Scotinophora lurida*, *S. coarctata*	Podopidae	Hemiptera	Major Pest
8	Earhead stink bug / Shield bug / Red spotted bug	*Menidahistrio*	Pentatomidae	Hemiptera	Minor Pest
9	Rice striped bug	*Tetrodahisteroides*	Pentatomidae	Hemiptera	Minor Pest
10	White rice leafhopper	*Cofana spectra*	Cicadellidae	Hemiptera	Minor Pest
11	Blue rice leafhopper	*Empoascanara maculifrons*	Cicadellidae	Hemiptera	Minor Pest
12	Zigzag striped leafhopper	*Recilia dorsalis*	Cicadellidae	Hemiptera	Minor Pest

2. Wheat

a. Termites – Odontotermes obesus (Isoptera: Termitidae)

Wheat, another vital cereal crop, is attacked by termites, primarily *Odontotermes obesus*, which belong to the order Isoptera and family Termitidae. These social insects form underground colonies and feed on root and stem tissues of the wheat plant, resulting in poor growth and drying. Their host range includes several field crops, and their distribution covers arid and semi-arid regions. The life cycle includes egg, nymph, and adult stages, with reproductive forms emerging seasonally. Colonies consist of workers, soldiers, and reproductive individuals.

b. Wheat aphid – Sitobionavenae

The wheat aphid, *Sitobionavenae*, from the order Hemiptera and family Aphididae, causes economic loss by sucking sap from the leaves and earheads. This aphid reproduces rapidly through parthenogenesis and has multiple generations per crop season. Heavy infestations can result in yellowing, curling, and poor grain filling. These aphids also serve as vectors of plant viruses, compounding their threat.

Table: Major and minor pests of wheat with their scientific names and classification

S. No.	Common Name	Scientific Name	Family	Order	Category
1	Wheat Aphid	*Macrosiphum miscanthi*	Aphididae	Hemiptera	Major Pest
2	Climbing cutworm / Armyworm	*Mythimna separata*	Noctuidae	Lepidoptera	Major Pest
3	Ghujhia Weevil	*Tanymecus indicus*	Curculionidae	Coleoptera	Major Pest
4	Gram Pod Borer	*Helicoverpa armigera*	Noctuidae	Lepidoptera	Major Pest
5	Termites	*Odontotermes obesus*, *Microtermesobesi*	Termitidae	Isoptera	Major Pest
6	Molya Nematode / Cyst Nematode	*Heteroderaavenae*	Heteroderidae	Tylenchida	Major Pest
7	Wheat-gall Nematode	*Anguina tritici*	Tylenchidae	Tylenchida	Major Pest
8	Aphids	*Schizaphisgraminum*, *Rhopalosiphummaidis*	Aphididae	Hemiptera	Minor Pest

9	Hopper	*Laodelphaxstriatella*, *Pyrillaperpusilla*	Delphacidae / Lophopidae	Hemiptera	Minor Pest
10	Jassids	*Amrasca* spp.	Cicadellidae	Hemiptera	Minor Pest
11	Wheat Bug	*Eurygastermaura*	Pentatomidae	Hemiptera	Minor Pest
12	Wheat Thrips	*Anaphothripsfavicinctus*	Thripidae	Thysanoptera	Minor Pest
13	Cutworms	*Agrotis* spp.	Noctuidae	Lepidoptera	Minor Pest
14	Leaf Folder	*Marasmiatrapezalis*	Pyraustidae	Lepidoptera	Minor Pest
15	Pink Borer	*Sesamia inferens*	Noctuidae	Lepidoptera	Minor Pest
16	Shootfly	*Atherigonanaqvii*, *A. oryzae*	Muscidae	Diptera	Minor Pest
17	Whorl Maggot	*Hydrelliagriseola*	Ephydridae	Diptera	Minor Pest
18	Flea Beetle	*Chaetocnema basalis*	Chrysomelidae	Coleoptera	Minor Pest

B. Pests of Pulses

1. Gram pod borer – Helicoverpa armigera (Lepidoptera: Noctuidae)

Among pulse crops, the gram pod borer, *Helicoverpa armigera*, is one of the most destructive pests. It belongs to the order Lepidoptera and family Noctuidae (Saxena *et.al.,* 2018). Its host range includes chickpea, pigeon pea, lentil, and several vegetables and oilseeds. The pest is distributed across temperate and tropical zones. Females lay eggs singly on floral parts, and the larva damages buds, flowers, and developing pods. A single larva can destroy multiple pods. The pest completes its life cycle in 30–40 days and has high reproductive potential.

2. Pulse beetle – Callosobruchus chinensis (Coleoptera: Bruchidae)

The pulse beetle, *Callosobruchus chinensis*, a member of the order Coleoptera and family Bruchidae, is a major pest of stored pulses such as chickpea, mung bean, and pigeon pea. Adults lay eggs on stored seeds, and upon hatching, the larva bores into the seed and feeds internally. The pest is capable of multiple generations under storage conditions, and each life cycle completes within 21–35 days. Infestation results in reduced seed viability, weight loss, and commercial devaluation.

3. Black aphid – Aphis craccivora (Hemiptera: Aphididae)

The black aphid, *Aphis craccivora*, classified under the order Hemiptera and family Aphididae, infests several pulse crops. This pest colonizes the undersides of young leaves and tender shoots, feeding on plant sap. Aphids also secrete honeydew that promotes the growth of sooty mold. They reproduce both sexually and asexually, leading to sudden population explosions under cool and moist conditions. Their ability to transmit viral pathogens further enhances their economic impact.

Table: Major and minor pests of leguminous crops (e.g., lablab/redgram) with their scientific names and classification

S. No.	Common Name	Scientific Name	Family	Order	Category
1	Bean Aphid	*Aphis craccivora*	Aphididae	Hemiptera	Major Pest
2	Thrips	*Ayyariachaetophora*, *Caliothrips indicus*, *Megalurothrips distalis*	Thripidae	Thysanoptera	Major Pest
3	Whitefly	*Bemisia tabaci*	Aleyrodidae	Hemiptera	Major Pest
4	Green Leafhopper	*Empoascakerri*, *E. binotata*, *E. flavescens*	Cicadellidae	Hemiptera	Major Pest
5	Pod Bug	*Riptortuspedestris*, *Clavigrallahorrens*, *C. gibbosa*, *Anoplocnemisphasiana*	Coreidae	Hemiptera	Major Pest
6	Lablab Bug / Stink Bug	*Coptosomacribraria*	Coremelanidae	Hemiptera	Major Pest
7	Leaf Webber	*Eucosmacritica*	Eucosmidae	Lepidoptera	Major Pest
8	Lab-lab Leaf Miner	*Cyphostichacoerula*	Gracillariidae	Lepidoptera	Major Pest

9	Termites	*Odontotermes obesus*	Termitidae	Isoptera	Major Pest
10	Redgram Scale	*Ceroplastodescajani*	Coccidae	Hemiptera	Minor Pest
11	Redgram Leaf Roller	*Caloptiliasoyella*	Gracillariidae	Lepidoptera	Minor Pest
12	Leaf Folder	*Anticarsiairrotata*	Noctuidae	Lepidoptera	Minor Pest
13	Leaf Eating Caterpillar	*Azaziarubricans*	Noctuidae	Lepidoptera	Minor Pest
14	Sphingid Caterpillar	*Acherontiastyx*	Sphingidae	Lepidoptera	Minor Pest
15	Leaf Cutter Bee	*Megachile anthracena*	Megachilidae	Hymenoptera	Minor Pest

C. Pests of Oilseeds

1. Mustard aphid – Lipaphiserysimi

The mustard aphid, *Lipaphiserysimi*, belongs to the order Hemiptera and family Aphididae (Gautam *et.al.,* 2019). It is a critical pest of oilseed brassicas such as mustard and rapeseed. These aphids feed on plant sap from tender parts, resulting in curling and drying of leaves and stunted growth. A single aphid can give birth to 30–50 nymphs in its lifetime. Colonies build up rapidly, especially during cooler months, and several overlapping generations may occur during the crop season.

2. Castor semilooper – Achaea janata

The castor semilooper, *Achaea janata*, a member of the order Lepidoptera and family Noctuidae, attacks castor and other crops. The larvae feed voraciously on leaves, often defoliating plants completely. The moth lays eggs on the underside of leaves, and the larval stage passes through five to six instars. Pupation occurs in the soil, and the complete life cycle takes 30–35 days.

D. Pests of Cotton

1. Cotton bollworms

a. Helicoverpa armigera

Cotton is affected by several bollworms, each differing in biology and impact. *Helicoverpa armigera* targets squares, flowers, and developing bolls.

Pectinophoragossypiella, or the pink bollworm, is known for its larval entry into cotton bolls, where it feeds on lint and seeds. It belongs to the order Lepidoptera and family Gelechiidae. Eggs are laid on bolls, and larvae burrow inside, making external detection difficult. Its life cycle lasts around 25–30 days.

b. Earias vittella (Spotted bollworm)

Earias vittella, the spotted bollworm, from the family Nolidae, is another major pest that affects tender shoots and bolls. The larvae bore into plant tissues and cause drying of shoots and rotting of bolls. All bollworms exhibit complete metamorphosis and multiple generations per crop season.

***2.* Whitefly – *Bemisia tabaci* (Hemiptera: Aleyrodidae)**

Among sucking pests, the whitefly, *Bemisia tabaci*, from the order Hemiptera and family Aleyrodidae, is highly destructive. It feeds on plant sap and excretes honeydew, leading to sooty mold development. It also transmits Cotton Leaf Curl Virus (CLCuV), a serious viral disease. Whiteflies reproduce through both sexual and parthenogenetic means and have high resistance to commonly used insecticides.

3. Jassid – *Amrasca Biguttula Biguttula*

The jassid, *Amrasca Biguttula Biguttula*, another sap-sucking pest from the family Cicadellidae, causes damage by feeding on the underside of cotton leaves. Infestation symptoms include leaf curling, yellowing, and leaf scorching. Nymphs and adults are both damaging stages. This pest breeds prolifically under warm, humid conditions and completes a generation in 10–14 days.

Table: Major and minor pests of cotton with their scientific names and classification

S. No.	Common Name	Scientific Name	Family	Order	Category
1	Leafhopper	*Amrascadevastans*	Cicadellidae	Hemiptera	Major Pest
2	Cotton Aphid	*Aphis gossypii*	Aphididae	Hemiptera	Major Pest
3	Thrips	*Thrips tabaci*	Thripidae	Thysanoptera	Major Pest
4	Whitefly	*Bemisia tabaci*	Aleyrodidae	Hemiptera	Major Pest
5	Mealy Bug	*Phenacoccussolani, Paracoccus marginatus*	Pseudococcidae	Hemiptera	Major Pest
6	Red Cotton Bug	*Dysdercuscingulatus*	Pyrrhocoridae	Hemiptera	Minor Pest
7	Dusky	*Oxycarenushyalinipennis*	Lygaeidae	Hemiptera	Minor

	Cotton Bug				Pest
8	Tobacco Cutworm	*Spodoptera litura*	Noctuidae	Lepidoptera	Minor Pest
9	Leaf Roller	*Syleptaderogata*	Pyraustidae	Lepidoptera	Minor Pest
10	Semiloopers	*Anomis flava*, *Xanthodesgraelsi*, *Tarachenitidula*	Noctuidae	Lepidoptera	Minor Pest
11	Stem Weevil	*Pempherulusaffinis*	Curculionidae	Coleoptera	Minor Pest
12	Shoot Weevil	*Alcidodesaffaber*	Curculionidae	Coleoptera	Minor Pest
13	Surface Weevil	*Attactogasterfinitimus*	Curculionidae	Coleoptera	Minor Pest
14	Black Scale	*Saissetia nigra*	Coccidae	Hemiptera	Minor Pest
15	White Scale	*Pulvinaria maxima*	Coccidae	Hemiptera	Minor Pest
16	Yellow Stem Scale	*Cerococcushibisci*	Asterolecanidae	Hemiptera	Minor Pest

E. Pests of Sugarcane

1. Early shoot borer – Chilo infuscatellus

Sugarcane cultivation is challenged by several borers. The early shoot borer, *Chilo infuscatellus*, is classified under the order Lepidoptera and family Crambidae. It damages young shoots by boring into the central whorl, causing dead hearts. The pest completes multiple generations per year, with larval and pupal stages spent within the stalk.

2. Top shoot borer – Scirpophagaexcerptalis

The top shoot borer, *Scirpophagaexcerptalis*, also from the Crambidae family, attacks the terminal shoots and emerging leaves of sugarcane. Larvae enter through

leaf sheaths and damage the central tissues, resulting in stunted cane growth. The pest is most active during warm and humid weather.

3. Root borer – Emmaloceradepressella

The root borer, *Emmaloceradepressella*, from the family Pyralidae, targets the root zone. Larvae feed on underground parts and cause yellowing and drying of shoots. The pest thrives in areas with well-irrigated soils and has a cryptic life habit that makes detection difficult.

F. Pests of Horticultural Crops

1. Fruit fly – Bactrocera spp. (Diptera: Tephritidae)

Among fruits and vegetables, the fruit fly, Bactrocera spp., belonging to the order Diptera and family Tephritidae, is one of the most serious pests (Sarwar *et.al.,* 2013). Species such as *Bactrocera dorsalis* attack mango, guava, citrus, and other fruits. Females lay eggs beneath the fruit skin, and maggots feed internally, leading to rotting and premature fruit drop. The pest's life cycle spans 15–25 days under optimal conditions.

2. Mango hopper – Idioscopus spp.

The mango hopper, Idioscopus spp., from the order Hemiptera and family Cicadellidae, is known for feeding on mango inflorescences and young leaves. Both nymphs and adults suck sap, leading to flower and fruit shedding. They also secrete honeydew, which supports fungal growth on panicles.

3. Brinjal shoot and fruit borer – Leucinodes orbonalis

The brinjal shoot and fruit borer, *Leucinodes orbonalis*, is a key pest of eggplant. It belongs to the order Lepidoptera and family Crambidae. Larvae bore into shoots and fruits, causing wilting and fruit damage. The pest completes its development in 21–30 days and can cause 70–80% yield loss under severe infestations.

4 Mealybug – Phenacoccussolenopsis

The mealybug, *Phenacoccussolenopsis*, from the order Hemiptera and family Pseudococcidae, is a polyphagous pest affecting crops such as cotton, tomato, and brinjal. It feeds on plant sap and forms white waxy colonies on tender plant parts. Reproduction is mainly parthenogenetic, and high humidity favors population buildup. Damage includes stunted growth, fruit deformation, and transmission of plant pathogens. These pests, through their varied feeding habits, reproductive strategies, and ecological adaptations, underscore the importance of understanding their scientific classification and bionomics for effective crop protection and sustainable pest management.

Host Range and Pest Adaptability

A. Host specificity vs. polyphagy

The host range of insect pests refers to the spectrum of plant species a particular pest can feed on and complete its life cycle. This range varies widely among pest species. Some insects exhibit high host specificity, feeding on a single crop or closely related species. For example, *Pectinophoragossypiella* (pink bollworm) is largely confined to cotton plants. Its entire developmental cycle, from egg to adult, is optimized for cotton, making it a monophagous pest. On the opposite end of the spectrum, many pests exhibit polyphagy, feeding on multiple, taxonomically unrelated host plants. *Helicoverpa armigera* is a prime example of a polyphagous pest, infesting more than 180 plant species, including cotton, chickpea, pigeon pea, tomato, sunflower, and maize. This adaptability enables such pests to survive across a variety of agroecosystems and persist even when primary host crops are not in season. Polyphagous pests tend to be more resilient to cropping pattern changes and pose a higher threat to food security due to their ability to exploit a broad range of cultivated and wild hosts.

B. Factors affecting host preference

Host preference in insect pests is determined by a complex interplay of morphological, biochemical, and ecological factors. The physical traits of the plant such as leaf texture, trichome density, and stem toughness influence the ability of insects to feed, lay eggs, or establish colonies. The jassid*Amrasca biguttula*prefers cotton varieties with sparse trichomes, as dense pubescence impedes nymphal movement and feeding. Nutritional composition is another major determinant. Plants rich in nitrogen, amino acids, or secondary metabolites attract specific herbivores. The mustard aphid *Lipaphiserysimi* exhibits a strong preference for succulent, nitrogen-rich young leaves of Brassica species. Volatile organic compounds emitted by plants also play a significant role in host selection, especially for moths and fruit flies that locate hosts through olfactory cues. Climatic conditions and crop phenology further influence host selection. Pests synchronize their feeding or oviposition behavior with the most susceptible crop stage, such as flowering or fruit setting, to maximize survival of their progeny. Behavioral learning and prior exposure also contribute to host fidelity, particularly in generalist feeders.

C. Examples of host shift in major pests

Host shift is the phenomenon where a pest expands its range to include new plant species, often due to ecological pressures or changes in cropping systems. This adaptive trait can lead to the emergence of new pest-crop interactions, complicating pest management efforts. A significant example is *Spodoptera frugiperda* (fall armyworm), which originally fed on maize but has now adapted to feed on rice, sorghum, sugarcane, and even vegetables like tomato. Its larval population has been recorded causing defoliation in several non-traditional host crops, indicating a high degree of ecological plasticity. Another case is *Bemisia tabaci* (whitefly), which historically preferred cotton but now heavily infests tomato, brinjal, and ornamental plants due to changes in planting patterns and continuous availability of suitable hosts. The whitefly's host shift is particularly concerning because of its capacity to transmit over 100 plant viruses, making it a vector of multiple diseases across unrelated crops. *Leucinodes orbonalis*, initially a brinjal-specific pest, has occasionally been observed on potato and tomato under high population pressure, though its performance on alternate hosts is often suboptimal.

These examples highlight how pests exploit new niches when environmental or cropping conditions favor expansion beyond their original host range. Host adaptability enhances the pest's survival and reproduction potential, often resulting in wider geographic spread and more complex pest management challenges. Understanding these dynamics is essential for predicting pest outbreaks and designing crop rotation strategies that minimize pest pressure across seasons.

Geographical Distribution of Key Pests

A. Agro-climatic regions and pest prevalence

The distribution of insect pests is strongly influenced by agro-climatic conditions such as temperature, humidity, rainfall, altitude, and soil type. These factors define the ecological boundaries within which specific pests can thrive and reproduce. Different agro-climatic zones support distinct pest complexes. In tropical and sub-tropical humid zones, pests like *Scirpophaga incertulas* (rice stem borer) and *Cnaphalocrocis medinalis* (rice leaf folder) are consistently prevalent due to the abundance of paddy fields and optimal moisture levels. Dry arid and semi-arid regions tend to support soil-dwelling pests such as *Odontotermes obesus* (termites) and *Trogoderma granarium* (khapra beetle), as these species are well adapted to low-moisture environments and sandy loam soils. Coastal agro-climatic zones with high humidity and dense vegetation create suitable conditions for pests like *Bemisia tabaci* (whitefly), which thrive under prolonged warm temperatures and high relative humidity. In high-altitude temperate zones, the prevalence of pests such as aphids and cutworms increases during cooler seasons, especially in horticultural crops like cabbage, cauliflower, and potato. Crop diversity and cropping intensity also affect pest distribution. Areas practicing intensive monocropping often experience high populations of host-specific pests due to continuous availability of food and habitat.

B. Influence of climate change on pest distribution

Changes in global and regional climate patterns have had significant impacts on the distribution, abundance, and behavior of agricultural pests (Porter *et.al.,* 1991). Rising temperatures, erratic rainfall patterns, extended droughts, and warmer winters have altered pest phenology and allowed range expansion into previously unsuitable regions. Higher temperatures accelerate the metabolic rate and reproduction in poikilothermic organisms such as insects. For example, *Spodoptera frugiperda* (fall armyworm), once restricted to tropical America, has expanded rapidly across continents. Warmer climates have enabled this pest to survive in non-traditional zones, completing more generations per year and causing heavier infestations. Similarly, *Helicoverpa armigera* populations have shown earlier emergence, higher fecundity, and extended flight activity under elevated temperatures. Climate variability also affects synchrony between pests and their natural enemies, often giving pests a reproductive advantage. Unseasonal rains and changes in humidity contribute to sudden outbreaks of sucking pests like *Aphis gossypii* and *Amrasca biguttulabiguttula*, which reproduce rapidly under mild, moist conditions. In mountain ecosystems, warming has led to the upward movement of pests into higher elevations, affecting crops that were earlier pest-free due to climatic barriers. Pest migration is now observed over longer distances due to altered wind currents, enabling rapid colonization of new regions. These shifts in pest dynamics necessitate re-evaluation of pest forecasting systems and location-specific management strategies.

C. Endemic vs. epidemic pests

Pests are categorized based on their distribution and outbreak behavior as either endemic or epidemic. Endemic pests are those that are consistently present in a particular region and cause damage at predictable levels year after year. These pests have stable interactions with their host plants and the local environment. Examples include *Pectinophoragossypiella* (pink bollworm) in cotton-growing areas and *Callosobruchus chinensis* in pulse storage zones. Their presence is linked with long-standing agricultural practices, local crop varieties, and persistent environmental conditions. Endemic pests typically do not cause sudden large-scale losses but can inflict chronic damage over time, reducing both yield and quality.

Epidemic pests, are not regularly present in an area but appear suddenly in massive numbers, often due to favorable climatic conditions, changes in cropping patterns, or breakdown of control measures. These outbreaks can result in severe and rapid crop destruction. An example is *Locusta migratoria* (desert locust), which under normal conditions exists in low numbers in isolated breeding grounds but can transition into gregarious swarms during periods of prolonged rainfall and vegetation growth. These swarms can travel hundreds of kilometers, devastating multiple crops in their path. Another example is the sporadic outbreak of *Spodoptera litura* on groundnut and soybean crops during periods of extended warm and wet weather. Epidemic pests often challenge traditional control systems and require immediate large-scale intervention, including aerial sprays and coordinated regional action. Monitoring climatic trends and pest population data is crucial for early detection and effective response to both endemic and epidemic pest threats.

Life Cycle and Seasonal Incidence

A. Description of developmental stages

The life cycle of insect pests comprises distinct stages of development, each with specific biological functions and ecological implications. Most economically important insect pests undergo either complete or incomplete metamorphosis. The primary stages include egg, larva or nymph, pupa in the case of holometabolous insects, and adult. Each stage contributes uniquely to the survival, dispersal, and reproductive success of the pest species.

1. Egg

The egg stage represents the beginning of the insect's life cycle. Female insects lay eggs either singly or in clusters on plant surfaces such as leaves, stems, fruits, or soil. Oviposition preferences vary depending on the species and environmental conditions. *Helicoverpa armigera* lays spherical, creamy-white eggs on tender floral parts, while *Bemisia tabaci* deposits eggs in a spiral pattern on the underside of leaves. Egg viability and hatchability are directly influenced by temperature and humidity. Under optimal conditions, the incubation period may last from 2 to 10 days. Eggs are immobile and serve as the initial phase for embryonic development.

2. Larva/Nymph

The larval or nymphal stage is the most active feeding phase and causes the majority of damage to crops. Larvae are characteristic of pests undergoing complete metamorphosis, such as *Spodoptera litura*, where the caterpillar has chewing mouthparts and feeds on leaves, stems, or fruits. Nymphs are present in insects with incomplete metamorphosis, such as *Nilaparvata lugens*, and resemble miniature adults. They possess piercing-sucking mouthparts and feed on plant sap. Larvae and nymphs pass through several molts, known as instars. The number of instars varies among species; for example, *Leucinodes orbonalis* larvae typically pass through five instars, while aphid nymphs undergo four. Feeding intensity and mobility during this stage determine the level of crop injury, making it a critical target for control measures.

3. Pupa (if applicable)

The pupal stage occurs in insects that undergo complete metamorphosis and serves as a transitional phase from larva to adult. This stage is non-feeding and usually occurs in protected environments such as soil, plant debris, silken cocoons, or inside host tissues. In *Pectinophoragossypiella*, pupation occurs inside cotton bolls, while *Spodoptera frugiperda* pupates in the soil. Duration of the pupal stage can range from 4 to 14 days, depending on environmental factors. Some species undergo prolonged pupal diapause during unfavorable seasons, resuming development when conditions improve. This stage contributes significantly to population survival and dispersal by enabling the insect to withstand climatic extremes.

4. Adult

The adult stage is responsible for dispersal and reproduction. Adults may be winged or wingless and exhibit varied behaviors such as nocturnal activity in moths or diurnal feeding in aphids and jassids. Adult longevity ranges from a few days to several weeks, depending on the species and availability of food and mates. *Bactrocera dorsalis* adults live for 30 to 90 days and continue to reproduce throughout their lifespan. Flight capability in adults plays a key role in colonizing new habitats, initiating fresh infestations, and escaping adverse conditions. The reproductive potential during this stage determines the rate of population increase and is a key factor in forecasting pest outbreaks.

B. Duration of life stages under different conditions

The duration of each developmental stage varies significantly with environmental conditions, especially temperature, relative humidity (RH), and host plant quality. Warmer temperatures generally accelerate development. *Spodoptera litura* completes its life cycle in 25 to 30 days under temperatures of 25–30°C, but development slows drastically at temperatures below 20°C. High humidity favors rapid development of sucking pests like whiteflies and aphids, whereas excessively dry conditions may hinder egg hatching and larval survival. Nutrient-rich host plants reduce the duration of larval stages due to improved feeding efficiency. Conversely, suboptimal host quality can lead to prolonged development or incomplete maturation. Understanding these stage-specific durations is essential for implementing control measures at the most vulnerable phase of the pest's life cycle.

C. Number of generations per year

The number of generations a pest completes in a year varies with species biology and environmental suitability. Multivoltine species, such as *Helicoverpa armigera*, may produce 5 to 8 generations annually. Rapid reproduction and overlapping generations allow populations to build up quickly, leading to persistent infestations. *Aphis craccivora* and *Bemisia tabaci* can produce over 10 generations per year under continuous cropping and mild climate conditions. Univoltine species like *Pectinophoragossypiella* in certain regions may have only one generation per year, particularly when diapause is involved. The voltinism of a pest species plays a critical role in designing pest management schedules, including timing of pesticide applications and deployment of biological control agents.

D. Factors influencing life cycle duration (temperature, RH, photoperiod)

Temperature exerts the most profound influence on insect development. Within a favorable thermal range, development rate increases with temperature (Shi *et.al.,* 2011). Below or above this range, development slows or ceases entirely. For example, the optimal temperature range for *Spodoptera frugiperda* development is between 25–30°C. Relative humidity affects survival and reproduction, particularly in sucking pests and egg viability. Low humidity levels may desiccate eggs or young nymphs, while high RH promotes soft-bodied insect survival. Photoperiod, or day length, influences diapause induction in species such as *Sesamia inferens* and *Chilo partellus*, where short day lengths and cooler temperatures signal the onset of developmental arrest. This seasonal dormancy enables pests to bridge unfavorable seasons and emerge synchronously with crop availability. Synchronization of pest life cycle with the phenological stages of host plants is a key adaptation that enhances feeding efficiency and survival. These interrelated factorsstage-specific biology, environmental parameters, and crop conditionsdetermine the seasonal incidence and population dynamics of insect pests. A comprehensive understanding of life cycle patterns and influencing variables is critical for forecasting pest outbreaks and implementing effective, timely control measures.

Bionomics and Pest Behavior

A. Feeding habits and damage symptoms

The feeding behavior of insect pests determines the type and severity of damage inflicted on crops. Pests exhibit various feeding mechanisms such as chewing, piercing-sucking, boring, mining, and rasping, each associated with characteristic symptoms. Chewing insects like *Spodoptera litura*, *Helicoverpa armigera*, and *Leucinodes orbonalis* consume foliage, flowers, and fruits, often leading to complete defoliation, flower drop, or internal fruit damage. Larvae of *Helicoverpa armigera* bore into flower buds and pods of chickpea and pigeon pea, causing poor seed setting and yield loss. Sucking pests such as *Bemisia tabaci*, *Aphis gossypii*, and *Amrasca biguttula*biguttula extract sap from phloem tissues, resulting in wilting, curling, yellowing, and stunted growth. Infestation by *Bemisia tabaci* is also associated with secretion of honeydew, which promotes the growth of sooty mold on leaves and fruits, reducing photosynthesis and marketability. Borers like *Chilo partellus* and *Scirpophaga incertulas* tunnel into stems, disrupting nutrient flow and causing “dead hearts” or “white heads” in cereals such as maize and rice. Leaf miners such as *Liriomyza trifolii* create serpentine mines within leaf tissues, reducing photosynthetic area and weakening plant vigor. The nature of feeding and damage caused varies with pest species, crop growth stage, and pest density, directly influencing both crop productivity and quality.

B. Pest survival and multiplication strategies

Pests have evolved numerous survival mechanisms that allow them to persist across seasons and adapt to adverse conditions. One such strategy is diapause, a physiological dormancy that enables insects to survive periods of extreme temperature or lack of food. *Pectinophoragossypiella* enters pupal diapause within cotton residues during offseason, resuming activity with the onset of the next cropping season. Another key survival method is polyphagy, where pests like *Spodoptera frugiperda* utilize multiple host plants, enabling year-round availability of food sources. Reproductive adaptations also enhance survival and multiplication. Aphids such as *Aphis craccivora* reproduce parthenogenetically, bypassing the need for males and rapidly increasing population within days. High fecundity is a common feature in moth species like *Spodoptera litura*, which lays 1000 to 1300 eggs per female, producing several generations in one season. Egg-laying behavior is also adapted for survival, as seen in pests like *Plutella xylostella* that prefer to lay eggs on the underside of leaves or in concealed plant crevices, protecting them from predators and environmental stress.

C. Behavioral adaptations (nocturnality, aggregation, etc.)

Behavioral traits play a crucial role in the success of insect pests in crop ecosystems. Nocturnality is a common adaptation observed in many lepidopteran pests such as *Helicoverpa armigera* and *Spodoptera litura*. Adults are primarily active during nighttime, engaging in mating and oviposition, which helps avoid detection and reduces predation risk. Larvae of these species often remain hidden under foliage or soil during daylight, emerging only at night to feed. Aggregation behavior is another notable trait, especially in pests like aphids and whiteflies, which form dense colonies on plant surfaces. This behavior enhances protection from natural enemies and facilitates easier transmission of plant viruses. Gregarious feeding in caterpillars such as *Achaea janata* allows them to defoliate plants quickly, overwhelming the host's defense systems. Certain pests show strong host-finding behavior guided by olfactory or visual cues. Fruit flies of the genus *Bactrocera locate* ripe fruits using volatile emissions, enabling precise oviposition that ensures food availability for emerging larvae. Shelter-seeking behavior is observed in stem borers and fruit borers that remain hidden within plant tissues, making external detection and control more difficult. These behavioral traits not only aid survival but also increase resistance to conventional control measures, including contact insecticides.

D. Interaction with natural enemies

In natural ecosystems, insect pests are part of complex food webs involving predators, parasitoids, and pathogens. Natural enemies play a significant role in regulating pest populations through biological control. Predators such as *Coccinella septempunctata* (ladybird beetle), *Chrysoperla carnea* (green lacewing), and syrphid fly larvae actively feed on aphids, jassids, and whiteflies, reducing pest densities during critical crop stages. Parasitoids like *Trichogramma chilonis* target the egg stage of pests including *Helicoverpa armigera*, preventing larval emergence and subsequent crop damage. Larval parasitoids such as *Campoletis chlorideae* lay eggs inside caterpillars, consuming the host from within. Entomopathogenic fungi (*Beauveria bassiana*), bacteria (*Bacillus thuringiensis*), and viruses (nuclear polyhedrosis virus) infect and kill insect pests through biological activity, especially under humid conditions. Pest behavior can affect interaction with natural enemies. Cryptic behavior and internal feeding by borers limit the effectiveness of predators and parasitoids. Conversely, the exposed feeding habits of leaf feeders make them more vulnerable to natural control agents. Maintaining biodiversity through reduced pesticide use and habitat management enhances the activity of beneficial organisms. Conservation of natural enemies forms a fundamental component of integrated pest management (IPM), contributing to sustainable control without chemical dependence. Understanding pest behavior in relation to their natural antagonists is crucial for designing effective biocontrol-based strategies and reducing pest resurgence.

Pest Monitoring and Identification Tools

A. Field scouting methods

Field scouting is the cornerstone of pest monitoring and plays a crucial role in early detection and timely management of insect pests. This process involves systematic field observations to record pest incidence, assess population density, and identify damage symptoms. The standard approach includes walking through crop fields in a zigzag or "X" pattern and inspecting randomly selected plants at different growth stages. Regular scouting intervals, usually weekly or biweekly, allow for the tracking of pest population trends across the crop cycle. For example, rice fields are examined for signs of stem borer infestation such as dead hearts and whiteheads, while cotton fields are monitored for the presence of bollworms, jassids, and whiteflies on leaves and bolls. Scouting is typically done during early morning or late afternoon when pests are more active and visible. Use of sweep nets, light traps, sticky traps, and pheromone traps complements visual inspection by capturing flying or nocturnal insects such as *Spodoptera litura*, *Helicoverpa armigera*, and *Bactrocera dorsalis*. Pheromone traps containing synthetic sex attractants are especially useful in estimating male moth populations and determining peak adult emergence periods. The data collected through scouting guides decisions regarding the need for control measures based on Economic Threshold Levels (ETL), reducing the indiscriminate use of pesticides and minimizing environmental risks.

B. Morphological keys and diagnostic features

Accurate identification of pest species is essential for implementing targeted and effective management strategies (Mehta *et.al.,* 2007). Morphological keys serve as standardized tools to distinguish among pest species based on physical characteristics such as body shape, coloration, wing structure, antennae type, mouthparts, and leg patterns. These taxonomic features are critical in differentiating between closely related species or pest and non-pest organisms. For example, *Bemisia tabaci* (whitefly) can be identified by its white waxy coating and horizontally held wings, whereas *Trialeurodes vaporariorum* (greenhouse whitefly) holds its wings more vertically. Among caterpillar pests, the V-shaped mark on the head capsule of *Spodoptera frugiperda* distinguishes it from other noctuid larvae. Similarly, aphids such as *Aphis craccivora* and *Myzus persicae* can be differentiated based on cornicle length, body color, and presence or absence of waxy secretions. In beetles, elytral markings and antennal segments are used for identification. Diagnostic features are observed using hand lenses, stereo microscopes, or portable magnifiers. Accurate morphological identification helps in avoiding misapplication of control measures and facilitates the selection of appropriate biocontrol agents or insecticides. It also supports pest surveillance, quarantine enforcement, and resistance monitoring programs.

C. Role of digital pest identification apps/tools

Advancements in information and communication technology have led to the development of digital tools that enhance pest identification and monitoring capabilities. Mobile-based applications and online platforms now offer real-time support for farmers, extension workers, and pest scouts. These tools integrate image recognition, geotagging, pest databases, and expert advisory systems. Applications such as e-Plant Clinics, Pest ID, and Plantix allow users to upload images of pests or damage symptoms, which are then analyzed using artificial intelligence algorithms or expert review. These tools provide identification within seconds and suggest immediate management recommendations based on pest biology, crop stage, and severity level. Geospatial pest mapping using GPS data enables regional forecasting of pest outbreaks and facilitates timely alerts to stakeholders. Digital platforms also support crowd-sourced data collection, where users contribute pest sightings that help in understanding population dynamics across regions. Integration of weather data with pest models through mobile apps has made it possible to predict the emergence of pests such as *Helicoverpa armigera* or *Bactrocera dorsalis*, improving the precision of interventions. Such digital innovations are transforming pest surveillance from reactive to predictive and preventive approaches. They are especially valuable in remote or underserved areas with limited access to entomological expertise, bridging the gap between field observations and scientific decision-making. Adoption of digital identification tools improves the accuracy, efficiency, and scalability of pest management systems in modern agriculture.

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Chapter 3

Pest Complexes and Management in Cereal and Pulse Crops

Sushant Kumar

Assistant Professor (Entomology), Faculty of Agricultural Sciences, GLA University, Mathura – 281 406 (U.P.)

Corresponding Author Email: Sushant.kumar@gla.ac.in

Cereals and pulses are fundamental to global food systems, serving as staple foods for billions of people and providing essential nutrients for human health. Cereals such as rice, wheat, maize, and sorghum are rich sources of carbohydrates, forming the bulk of caloric intake in many diets. Pulses like chickpea, pigeon pea, lentil, and green gram are highly valued for their protein content, dietary fiber, vitamins, and micronutrients, particularly iron and folate. These crops contribute significantly to nutritional security by complementing each other in terms of amino acid profiles when consumed together. Cereals and pulses are also vital for soil fertility and sustainable farming systems. Pulses enhance nitrogen availability through biological fixation, reducing the need for synthetic fertilizers and improving soil health for subsequent crops. As demand for food rises with increasing population, the importance of cereals and pulses in ensuring food availability, reducing malnutrition, and supporting agroecological balance continues to grow.

A. Pest problems in cereal and pulse production

Cereal and pulse crops are frequently exposed to a wide range of arthropod pests that cause substantial losses at various stages of crop growth (Yaseen *et.al.,* 2019). In cereals, pests such as stem borers (*Scirpophaga incertulas*, *Chilo partellus*), leaf folders (*Cnaphalocrocis medinalis*), brown planthopper (*Nilaparvata lugens*), and fall armyworm (*Spodoptera frugiperda*) attack the vegetative and reproductive structures, leading to yield losses that can range from 10% to 70% under severe infestation. In pulses, *Helicoverpa armigera* remains the most destructive pest, affecting chickpea and pigeon pea pods and causing crop loss of 20% to 50% annually. Other pests such as aphids (*Aphis craccivora*), pod fly (*Melanagromyza obtusa*), and cutworms (Agrotis spp.) also contribute to damage in both vegetative and reproductive phases. These pests not only reduce yields but also affect the quality and marketability of produce. Increased pest pressure, combined with changing climatic patterns, monocropping practices, and pesticide misuse, has resulted in pest outbreaks, resistance development, and resurgence. The losses extend to post-harvest stages as well, particularly in pulses and maize, where storage pests like *Sitophilus oryzae* and *Callosobruchus chinensis* cause significant damage to stored grains, leading to both quantitative and qualitative losses.

B. Need for integrated pest management (IPM) in these crops

The increasing incidence of pest-related losses in cereal and pulse crops has highlighted the limitations of sole reliance on chemical control. The overuse and misuse of pesticides have led to the development of resistance in major pests, destruction of beneficial natural enemies, environmental contamination, and health risks to farmers and consumers. Integrated Pest Management (IPM) offers a holistic and sustainable approach to address these challenges. IPM incorporates multiple pest control strategies, including cultural practices such as crop rotation and timely sowing, biological control using parasitoids, predators, and entomopathogens, resistant crop varieties, and the judicious use of pesticides based on economic thresholds. This approach reduces the dependence on chemical inputs while ensuring economic viability and environmental safety. Adoption of IPM also enhances biodiversity, strengthens agroecosystem resilience, and contributes to long-term sustainability in cereal and pulse production systems. As these crops are central to both food and nutritional security, implementing IPM at the field level is critical for safeguarding yields, improving farm incomes, and promoting safe and sustainable agricultural practices.

Major Pests of Rice

A. Stem borers (*Scirpophaga incertulas*, *Chilo suppressalis*)

Stem borers are among the most economically damaging pests of rice, attacking the crop from the seedling to the heading stage. The yellow stem borer (*Scirpophaga incertulas*) and striped stem borer (*Chilo suppressalis*) are the two most prevalent species. These larvae bore into the stem of rice plants and feed internally, causing characteristic symptoms such as “dead hearts” during the vegetative stage and “whiteheads” during the reproductive phase. Dead hearts result from larval feeding on the growing shoot, leading to yellowing and drying of the central tiller, while whiteheads occur when the panicle emerges but remains blank due to disruption of nutrient flow. Yield losses caused by stem borers can range from 10% to as high as 60% under severe infestation, depending on the stage of attack and crop variety.

B. Leaf folder (*Cnaphalocrocis medinalis*)

Leaf folder larvae fold rice leaves longitudinally and feed from within, scraping the green tissue and leaving behind a transparent epidermis. This feeding reduces the leaf’s photosynthetic area and weakens the plant, particularly during the tillering and booting stages. Heavy infestations result in large-scale leaf damage and poor grain development. A single larva may damage multiple leaves during its life span, and under conducive weather conditions, such as high humidity and moderate temperatures, the pest can multiply rapidly. Yield reduction due to leaf folder damage has been reported to range between 10% and 40% depending on crop stage and infestation level.

C. Brown planthopper (*Nilaparvata lugens*)

The brown planthopper (BPH) is a major sap-sucking pest that affects rice by feeding on the phloem sap at the base of the plant. Heavy infestations lead to "hopper burn," a condition where leaves turn yellow or brown and the entire plant dries out, often resulting in complete crop failure in patches or entire fields. BPH also acts as a vector of viral diseases such as grassy stunt and ragged stunt viruses, compounding the damage. This pest thrives under dense planting and high nitrogen fertilization. Under epidemic conditions, BPH can reduce yields by up to 80%, especially in high-yielding susceptible varieties. The pest's ability to develop resistance to multiple insecticides has made its management particularly challenging.

D. Green leafhopper (*Nephotettix virescens*)

Green leafhoppers are small, mobile insects that feed on rice leaves and also serve as vectors for tungro virus, one of the most serious viral diseases affecting rice. While direct feeding causes limited damage, the transmission of rice tungro bacilliform virus (RTBV) and rice tungro spherical virus (RTSV) results in stunted plant growth, yellow to orange leaf discoloration, and significantly reduced tillering. Tungro disease leads to 5% to 70% yield loss depending on the timing of infection and susceptibility of the variety. Leafhopper populations increase rapidly in warm, humid climates, especially during early crop growth stages when the crop is more vulnerable.

E. Gall midge (*Orseolia oryzae*)

The rice gall midge is another important pest that causes damage by inducing gall formation at the base of the tiller (Bentur *et.al.,* 2016). The maggot, which hatches from eggs laid near the leaf sheath, migrates to the growing point and feeds on meristematic tissues. This feeding results in the formation of a tubular outgrowth known as a "silver shoot," which is incapable of producing a panicle. Infestations can occur as early as the seedling stage and may persist up to the late vegetative stage. Yield losses due to gall midge vary from 10% to 40%, but in certain outbreak conditions, especially in monsoon-planted crops, the damage can be more extensive.

F. Caseworm (*Nymphula Depunctalis*)

The rice caseworm is a semi-aquatic pest whose larvae build portable cases from leaf material and feed on leaf tissues while submerged in water. It typically attacks rice in nursery and early transplanted stages. The larvae cut leaf blades and leave behind only the midrib, leading to a "ladder-like" appearance in affected leaves. Heavy infestation can reduce seedling vigour and delay transplanting schedules. Caseworm damage is particularly severe in poorly drained fields with continuous standing water. Although less destructive than other major pests, in localized outbreaks, yield losses can still be significant, particularly when young plants are heavily defoliated.

G. Integrated Pest Management Strategies in Rice

1. Monitoring and threshold levels

Management of rice pests requires a holistic approach that balances pest suppression with environmental and economic sustainability. Monitoring pest populations through field scouting, pheromone traps, and light traps is the foundation of any integrated pest management (IPM) strategy. Economic threshold levels (ETLs) are established for each pest to guide timely interventions. For example, the ETL for yellow stem borer is one egg mass per square meter or 10% dead hearts in the field.

2. Cultural practices (synchronous planting, spacing)

Synchronous planting within a locality helps break the pest life cycle and limits continuous host availability. Maintaining optimal plant spacing reduces humidity and improves aeration, which discourages the buildup of pests like leaf folder and BPH. Timely sowing and water management also play key roles in pest avoidance.

3. Biological control (natural enemies, parasitoids)

Several natural enemies such as egg parasitoids (*Trichogramma japonicum*), predators like *Cyrtorhinus lividipennis* (mirid bug), and spiders (*Lycosa pseudoannulata*, *Tetragnatha* spp.) are important in suppressing rice pest populations. Conservation of these biocontrol agents through habitat management and reduced pesticide use enhances their effectiveness. Augmentative release of parasitoids is practiced in certain rice-growing regions as part of bio-intensive IPM.

4. Resistant varieties

Breeding and deployment of pest-resistant varieties remain a cornerstone of pest management. Varieties such as IR64 and Swarna have shown moderate resistance to stem borers and planthoppers. Resistance to tungro virus and gall midge has also been incorporated into some improved cultivars, providing a non-chemical, long-term solution to pest pressure.

5. Need-based chemical control

Chemical insecticides are applied only when pest populations exceed the economic threshold level. Selective insecticides that are less harmful to natural enemies are preferred. Cartap hydrochloride and chlorantraniliprole are recommended for stem borers, while buprofezin and flonicamid are effective against sucking pests like BPH. Tank-mixing of insecticides is discouraged to prevent resistance development and safeguard beneficial organisms. Effective management of rice pests involves a combination of these strategies, tailored to local agroecological conditions and pest incidence patterns. A well-implemented IPM approach not only preserves yield but also promotes sustainability and economic efficiency in rice cultivation.

Major Pests of Wheat

A. Aphids (*Schizaphis graminum, Rhopalosiphum maidis*)

Aphids are among the most common and economically significant sucking pests of wheat. *Schizaphis graminum* and *Rhopalosiphum maidis* colonize the undersides of leaves, leaf sheaths, and earheads, especially during the late tillering to grain-filling stages. These insects feed on phloem sap using their piercing-sucking mouthparts, leading to symptoms such as leaf curling, yellowing, and wilting. Heavy infestations reduce plant vigour, interfere with nutrient translocation, and impair grain development. Aphids also secrete honeydew, which promotes the growth of sooty mold and reduces photosynthetic activity. In many wheat-growing regions, aphid populations can escalate rapidly during warm and dry conditions. Yield losses range from 10% to 40% depending on pest density and duration of attack. Aphids are also vectors of viral diseases such as barley yellow dwarf virus, which further exacerbates yield loss and affects grain quality.

B. Termites (*Odontotermes* spp., *Microtermes* spp.)

Termites are subterranean pests that damage wheat by feeding on root systems, stem bases, and occasionally lower leaf sheaths. *Odontotermes* and *Microtermes* species are commonly associated with wheat crop damage, particularly in fields with a history of infestation or poor organic matter management. These pests weaken plants by disrupting water and nutrient uptake, leading to wilting, lodging, and plant death. Damage is often patchy but can become widespread under drought conditions or in sandy loam soils, where termites thrive. Infestation during the early vegetative stage can result in plant mortality and significant yield reduction. Termite incidence is closely linked to soil health, organic residue accumulation, and moisture stress. Losses due to termites vary between 5% and 25%, with higher damage observed in untreated or poorly managed fields.

C. Armyworm (*Mythimna separata*)

The armyworm, *Mythimna separata*, is a defoliating pest that primarily attacks wheat during the early growth stages. The larvae emerge in large numbers and feed gregariously on leaves, often leaving only midribs and stalks behind. The name "armyworm" refers to the pest's habit of moving in large masses from one field to another. Outbreaks usually occur during humid conditions following rainfall or irrigation. Armyworm larvae are nocturnal feeders and hide in soil during the day, which makes detection difficult during the initial stages of infestation. Crop losses can range from 15% to 40% depending on larval density and crop stage. Heavy defoliation reduces photosynthetic capacity, delays maturity, and results in poor grain filling and shriveled kernels.

D. Pink stem borer (*Sesamia inferens*)

Sesamia inferens, commonly known as the pink stem borer, attacks wheat at the tillering and booting stages. The larvae bore into the stem at the base, feeding on the internal tissues and disrupting vascular connections. This results in drying of central shoots and formation of dead hearts. During reproductive stages, infestation may cause incomplete panicle emergence or whiteheads similar to symptoms observed in rice. The pest survives in crop residues and alternate hosts such as maize and sorghum, allowing year-round presence. Damage is often observed in late-sown wheat or in fields with dense canopy and high soil moisture. Losses due to pink stem borer vary from 10% to 30%, with more severe effects on poorly managed crops or delayed sowings.

E. Shoot fly (*Atherigona naqvii*)

Shoot fly is an early-season pest that affects wheat during seedling and early tillering stages (Leybourne *et.al.,* 2024). The adult female lays eggs on the young seedlings, and upon hatching, the maggots penetrate into the central shoot and feed on the growing point, resulting in the formation of dead hearts. The affected tillers dry out, remain stunted, and do not produce grain. Late-sown wheat is more susceptible to shoot fly damage due to increased overlap with peak fly activity. Infestation can lead to poor crop stand and significant yield reductions, especially in regions where early sowing is not practiced. Estimated yield loss can range from 5% to 35%, depending on sowing date, plant density, and local climate.

F. Integrated Pest Management in Wheat

A comprehensive IPM approach is essential for minimizing pest-induced losses in wheat and ensuring sustainable crop production. Management begins with preventive measures such as seed treatment and soil preparation.

1. Seed treatment and soil management

Seed treatment with insecticides like imidacloprid or clothianidin protects seedlings from early-season pests such as termites and shoot flies. Healthy seed emergence and vigorous plant growth serve as the first line of defense against pest invasion. Maintaining soil health through organic amendments and residue management helps reduce termite activity and encourages the presence of beneficial soil organisms.

2. Early sowing and crop rotation

Timely sowing of wheatpreferably before the second fortnight of Novemberreduces exposure to shoot fly and armyworm infestations. Crop rotation with non-host crops such as legumes interrupts pest life cycles, especially those of stem borers and termites, and improves soil fertility. Intercropping or strip cropping may also create unfavorable conditions for pest colonization and movement.

3. Use of bioagents and natural predators

Biological control plays a vital role in wheat pest management. Natural predators like ladybird beetles (*Coccinella septempunctata*), lacewings (*Chrysoperla carnea*), and hoverflies suppress aphid populations effectively. Entomopathogenic fungi such as Beauveria bassiana and Metarhizium anisopliae are used in some regions to target termites and armyworms. Conservation of these biocontrol agents is achieved through reduced pesticide use and habitat management strategies.

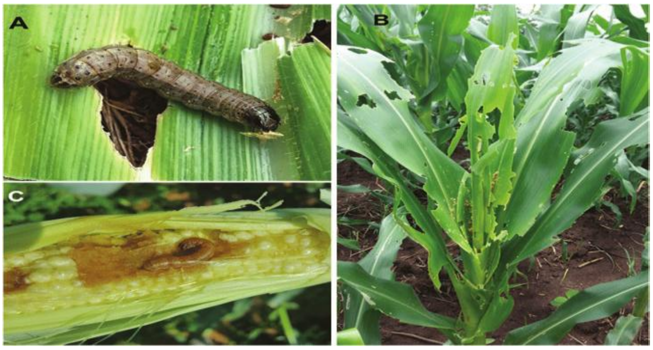
4. ETL-based insecticide application

Pesticides are applied only when pest populations cross economic threshold levels. For aphids, the ETL is typically 10–15 aphids per tiller during the grain formation stage. For armyworm, control is recommended when 1–2 larvae per square meter are observed. Spray decisions based on these thresholds help prevent unnecessary chemical applications and reduce the risk of resistance and resurgence. Selective insecticides with minimal impact on beneficial organisms are preferred for sustaining long-term control. The adoption of integrated pest management in wheat enables cost-effective, environmentally sound, and efficient pest control. A well-executed IPM plan not only reduces pest pressure and yield loss but also promotes ecosystem stability and improves farmer profitability.

Major Pests of Maize

A. Fall armyworm (*Spodoptera frugiperda*)

Fall armyworm is a polyphagous pest native to the Americas and has emerged as one of the most invasive and destructive pests of maize globally. The larvae of *Spodoptera frugiperda* feed voraciously on maize leaves, whorls, tassels, and developing cobs. Damage begins with windowpaning symptoms on young leaves, progressing to large irregular holes and shredded whorls as larvae mature. The pest’s ability to reproduce rapidly, migrate long distances, and complete multiple generations in a single season allows for explosive population build-up under favorable conditions. Each female can lay up to 1,500 eggs in her lifetime. In maize, yield losses due to fall armyworm can reach 50% or more under severe infestation. The pest's cryptic larval stages within the whorl make control difficult using contact insecticides, necessitating systemic or biological approaches.



B. Stem borer (*Chilo partellus*)

Chilo partellus is a major lepidopteran pest of maize and sorghum that damages the crop from seedling to maturity. Larvae bore into the central stem, feeding on internal tissues and disrupting nutrient and water translocation. Early attack causes dead heart formation, where the central shoot wilts and dies. In older plants, the damage reduces ear development and grain filling. The larval tunneling also weakens the stem, making plants prone to lodging. A single larva can tunnel through several centimeters of stem, and multiple larvae in a plant can lead to extensive internal destruction. Yield losses vary from 15% to 40% depending on infestation level and crop stage at the time of attack. The pest is more active during warm and dry conditions, especially in monocropped maize fields.

C. Shoot fly (*Atherigona* spp.)

Shoot flies, particularly *Atherigona orientalis and Atherigona soccata*, attack maize at the seedling stage and can be highly damaging under delayed or staggered planting (Salman *et.al.,* 2008). Female flies lay eggs on the undersides of young leaves, and upon hatching, maggots bore into the growing point of the plant. This results in the death of the central shoot, forming the classic "dead heart" symptom. Damaged plants often produce side tillers, which are unproductive and lead to poor stand establishment and yield loss. Infestation is more severe in late-sown crops and in fields lacking synchronized germination. Losses from shoot fly range from 10% to 60%, particularly in areas with erratic rainfall or extended planting windows.

D. Corn aphid (*Rhopalosiphum maidis*)

Corn aphid is a sap-sucking insect that colonizes the whorls, leaves, tassels, and earheads of maize plants. It thrives in warm, dry conditions and multiplies rapidly through parthenogenesis. Aphids remove plant sap, inject toxic saliva, and excrete honeydew that leads to the development of sooty mold. This reduces photosynthesis and affects the quality of developing grains. Heavy infestations can lead to leaf curling, stunted growth, and poor ear formation. Aphids also act as vectors for viral diseases such as maize dwarf mosaic virus. Though less damaging than foliar feeders or borers, corn aphids can still cause economic yield losses, particularly in high-density plantings or under stress conditions. Yield losses of 10% to 25% have been recorded in aphid-affected crops with delayed detection or inadequate control.

E. Termites

Termites are soil-dwelling insects that attack maize roots, basal stems, and sometimes ear husks. Their damage is typically observed in older plants and during periods of drought or low soil moisture. Termites feed on cellulose and can cause lodging by hollowing out the stem base. The infestation often begins in localized patches and can spread if conditions remain conducive. Losses depend on the extent of infestation and may range from 5% to 20%, particularly in sandy or low-organic matter soils. Continuous maize cropping, poor residue management, and lack of deep tillage promote termite survival and resurgence. Infestation is more common during the rabi season or in areas with minimal rainfall.

F. Integrated Pest Management in Maize

Effective maize pest control relies on integrating cultural, biological, and chemical methods to reduce pest pressure and enhance crop resilience. Deep summer ploughing is a preventive strategy that exposes pest pupae and larvae to desiccation and predation. This is especially effective against shoot fly and stem borer, as it disrupts their life cycles and reduces initial inoculum in the field.

1. Deep summer ploughing and early planting

Ploughing during peak summer helps destroy soil-dwelling stages of pests like *Chilo partellus* and Atherigona spp. Early planting allows maize to escape peak pest incidence, particularly shoot fly, whose population peaks during the late sowing window. Sowing before the third week of June has been shown to reduce shoot fly infestation by more than 50% in multiple field trials.

2. Use of pheromone traps and light traps

Pheromone traps are employed to monitor and suppress moth populations of fall armyworm and stem borers. Each trap can attract hundreds of male moths, providing early warning signals and population data for decision-making. Light traps are useful for general surveillance of nocturnal pests and can assist in controlling adult moths before egg-laying occurs.

3. Conservation of biocontrol agents

Biological control plays a critical role in maize pest management. Egg parasitoids like *Trichogramma chilonis* and larval parasitoids such as Cotesia flavipes are effective against *Chilo partellus*. *Telenomus remus* has been used successfully against fall armyworm in several locations. Predators such as ladybird beetles and lacewings also help reduce aphid populations. Avoiding broad-spectrum insecticides and preserving flowering plants around field margins supports the conservation of these natural enemies.

4. Use of resistant hybrids and seed treatment

Growing resistant or tolerant maize hybrids significantly reduces vulnerability to key pests. Some hybrids have tighter whorl architecture or faster early growth, which makes them less attractive to early-stage pests like fall armyworm and shoot fly. Seed treatment with systemic insecticides such as thiamethoxam or imidacloprid protects seedlings for the first three to four weeks after germination, reducing early pest establishment. This window is critical, as most severe damage occurs during the early vegetative phase. Integrated pest management in maize emphasizes timely interventions based on pest monitoring, resistant cultivars, natural enemy preservation, and threshold-based pesticide use. This strategy not only lowers production costs and pesticide load but also ensures a stable yield and healthier agroecosystem. The success of maize cultivation under increasing biotic stress depends heavily on implementing IPM at the farmer field level with proper technical support and timely advisories.

Major Pests of Sorghum

A. Shoot fly (*Atherigona soccata*)

Shoot fly is the most destructive early-season pest of sorghum and causes severe damage to seedlings and young plants. The adult fly lays eggs on the undersides of the first few leaves shortly after germination. The maggots that hatch from these eggs enter the central whorl and damage the growing point, resulting in the formation of "dead hearts." These dead hearts are characterized by dried central shoots that can be easily pulled out. A single female fly is capable of laying over 30 eggs in her lifespan, and damage is most severe when sowing is delayed beyond the optimum window. Late-sown crops face higher infestation due to synchronization of peak pest activity with early crop stages. Under high shoot fly pressure, plant stand establishment is significantly affected, leading to yield losses that can range between 30% and 80%, especially in rainfed conditions or when sowing is staggered.

B. Stem borer (*Chilo partellus*)

Chilo partellus is a lepidopteran borer that attacks sorghum at both vegetative and flowering stages (Sau *et.al.,* 2022). The larvae bore into the stem and feed on internal tissues, which interrupts water and nutrient flow and reduces plant vigour. Early infestations lead to dead hearts, while in older plants, larval tunneling results in poor panicle development, reduced grain filling, and increased susceptibility to lodging. Yield losses from stem borer attack can vary from 20% to 50% depending on the crop stage, variety, and extent of damage. The pest thrives in dry climates and poorly managed fields with crop residues left behind, which serve as a source of infestation for the next season. Its wide host range, including maize and other grasses, enables its persistence across cropping systems.

C. Midge (*Stenodiplosis sorghicola*)

The sorghum midge is a tiny fly whose larva damages the crop by feeding inside developing florets. The female midge lays eggs in open florets during flowering, and the maggots feed on the developing ovary, preventing seed formation. Infested spikelets fail to produce grain, resulting in empty glumes that give the panicle a partially filled or blasted appearance. Damage is particularly severe during warm and humid weather, and under outbreak conditions, yield losses can reach up to 70%. The short lifecycle and multiple generations of the midge allow rapid population build-up, especially when the flowering period is extended due to staggered sowing. Fields with mixed panicle maturity or delayed flowering are more prone to heavy damage.

D. Armyworm (*Mythimna separata*)

Armyworm larvae are voracious feeders that attack sorghum foliage in mass outbreaks, particularly during the early vegetative stage. The caterpillars feed on leaf margins and move from plant to plant, leaving behind only leaf midribs. Severe defoliation reduces the photosynthetic area, delays crop development, and lowers grain yields. The pest is migratory and is known to appear suddenly following spells of rain after dry weather. Armyworm outbreaks are often observed in moist lowland fields and regions receiving late monsoon rains. Yield losses due to armyworm range from 15% to 40%, and the economic impact is more severe in poorly monitored or unattended fields.

E. Integrated Pest Management in Sorghum

Effective management of sorghum pests relies on preventive cultural practices, ecological interventions, and targeted use of biopesticides or insecticides. The timing of sowing plays a critical role in avoiding major pest damage.

1. Adjustment of sowing time

Timely sowing of sorghum, particularly in the first fortnight of the monsoon onset, helps avoid peak shoot fly incidence. When sowing is delayed, the crop becomes more vulnerable to early-season pests such as shoot fly and stem borer. Sowing during the recommended window also ensures more synchronized flowering, reducing the risk of midge damage.

2. Destruction of crop residues

Proper field sanitation, including the removal and destruction of leftover stalks and panicles after harvest, helps in reducing the carryover population of borers and midges. Crop residues often harbor pupae or diapausing stages that initiate fresh infestations in the following season. Deep ploughing during the off-season exposes and kills pest stages present in the soil or plant debris.

3. Intercropping and trap crops

Intercropping sorghum with legumes like cowpea or pigeon pea can reduce the incidence of pests through altered crop microenvironment and increased activity of natural enemies. Trap crops such as maize or fodder sorghum planted around the main field help divert stem borers and shoot flies away from the main crop. This approach, combined with regular monitoring, enhances the effectiveness of pest management.

4. Biopesticides and selective insecticides

Biopesticides such as *Bacillus thuringiensis* (Bt) and neem-based formulations are effective against early larval stages of borers and armyworms. Egg parasitoids like *Trichogramma chilonis* and larval parasitoids such as Cotesia flavipes are used to suppress *Chilo partellus* populations. For shoot fly and midge, seed treatment with systemic insecticides such as imidacloprid or clothianidin provides protection during the vulnerable seedling stage. In cases where pest populations cross economic thresholds, selective insecticides such as spinosad, emamectin benzoate, or chlorantraniliprole are applied with care to minimize harm to beneficial organisms. Integrated pest management in sorghum emphasizes preventive strategies and ecological balance to reduce dependence on chemicals. Early detection through field scouting, use of pest-resistant varieties, and informed timing of interventions ensure minimal crop loss and contribute to sustainable sorghum production systems.

Major Pests of Chickpea

A. Pod borer (*Helicoverpa armigera*)

Pod borer, *Helicoverpa armigera*, is the most destructive pest of chickpea and accounts for major crop losses during the flowering and pod development stages. The pest causes damage by feeding on flower buds, developing pods, and seeds. The female moth lays eggs singly on floral parts, and the larvae, upon hatching, bore into the pods and consume the seeds, often damaging multiple pods during their life cycle. A single larva can destroy 30 to 40 pods, depending on its stage and duration of feeding. Yield losses from pod borer range from 15% under low infestation to more than 50% during severe outbreaks. The pest has a high reproductive capacity, multiple generations per season, and a wide host range that includes pigeon pea, tomato, and cotton, making its management challenging. Resistance to several classes of insecticides has also been reported, increasing the importance of non-chemical control methods.

B. Cutworms (*Agrotis Ipsilon*)

Cutworms are nocturnal pests that cause damage during the seedling and early vegetative stages of chickpea. The larvae remain hidden in the soil during the day and come out at night to feed. They typically cut young plants at the base near the soil surface, leading to wilting and plant death. The greyish-black larvae of Agrotis Ipsilon are particularly destructive when the crop is sown in fields with grassy weeds or stubble, which support larval development before chickpea emergence. Cutworm infestations are generally patchy, but under favorable conditions, losses can reach up to 30%, especially when seedling mortality is high and the crop fails to establish a uniform stand. Moist soil and cloudy weather increase cutworm activity, and sandy soils are more prone to harboring larvae.

C. Aphids (*Aphis craccivora*)

Aphis craccivora is a soft-bodied, sap-sucking insect that colonizes the tender parts of chickpea plants, particularly the terminal shoots and young leaves. Aphids remove plant sap using their piercing-sucking mouthparts, leading to leaf curling, yellowing, and reduced plant vigour. They also excrete honeydew, promoting the growth of black sooty mold that interferes with photosynthesis. The pest reproduces parthenogenetically and builds up populations rapidly during cool and dry weather. Apart from direct feeding, aphids are known to transmit viruses such as chickpea stunt disease, which results in stunted growth, reddening of leaves, and poor pod setting. Yield losses from aphid infestation range between 10% and 35%, with virus transmission contributing to more severe reductions.

D. Leaf miner (*Liriomyza cicerina*)

Leaf miner larvae feed between the upper and lower epidermal layers of chickpea leaves, creating characteristic serpentine mines. The adult is a small fly that lays eggs within the leaf tissue, and the emerging larvae tunnel through the mesophyll, destroying chlorophyll-containing cells. Infested leaves show white or yellow mining trails that reduce the photosynthetic area and impair plant growth. Severe infestations may lead to premature leaf drop and poor pod formation. Leaf miner populations typically peak during the vegetative to flowering stage, particularly under warm and dry conditions. Yield reductions can reach 15% to 25% depending on infestation intensity and crop variety.

E. Integrated Pest Management in Chickpea

Managing chickpea pests effectively requires a comprehensive strategy that integrates host plant resistance, agronomic practices, biological control, and judicious pesticide application based on economic thresholds. The use of pest-resistant chickpea varieties plays a central role in reducing pod borer and aphid damage. Varieties such as ICCV 10 and JG 11 have shown moderate resistance to pod borer infestation and are widely promoted in areas facing recurrent outbreaks.

1. Use of resistant varieties

Resistant cultivars possess morphological or biochemical traits that deter pest establishment or feeding (Rizwan *et.al.,* 2021). Hairy pod surfaces, thicker pod walls, and high phenolic content are some features that discourage larval entry and reduce feeding efficiency. Growing such varieties helps lower pest density and minimizes the need for frequent insecticide applications.

2. Timely sowing and intercropping

Sowing chickpea at the appropriate time reduces exposure to peak pest activity. Early sowing, particularly in the second half of October, helps the crop escape the reproductive stages of *Helicoverpa armigera*, which coincide with higher temperatures and greater pest activity in late-planted crops. Intercropping chickpea with crops such as linseed or mustard alters the crop microclimate and reduces pest colonization. Border crops act as physical barriers and attract natural enemies, enhancing biological control.

3. Biological control using NPV, Trichogramma

Biological agents offer an eco-friendly alternative for managing major chickpea pests. The Helicoverpa nuclear polyhedrosis virus (HaNPV) is a highly effective biopesticide used to target early instar larvae of pod borer. It infects and kills the larvae within 4 to 7 days after ingestion. Mass production and field application of HaNPV are promoted through farmer cooperatives and extension services. Egg parasitoids such as *Trichogramma chilonis* are released to reduce the population of *Helicoverpa armigera* by parasitizing their eggs before larval emergence. Predatory insects such as ladybird beetles and green lacewings also play a role in aphid suppression.

4. Economic threshold-based chemical control

Chemical insecticides are used when pest populations exceed economic threshold levels. For pod borer, the threshold is one larva per plant or 5–10% pod damage. For aphids, action is recommended when more than 15 aphids per plant are observed on 10% of plants. Insecticides such as spinosad, emamectin benzoate, and flubendiamide are preferred due to their selectivity and effectiveness against lepidopteran pests. Systemic insecticides like imidacloprid are applied for aphid control. All chemical applications must be timed to target the most vulnerable pest stages and avoid harm to pollinators and natural enemies. The integration of resistant varieties, ecological practices, biocontrol agents, and need-based pesticide use enables sustainable chickpea production with minimal environmental impact. A successful IPM approach improves yield stability, reduces costs, and supports long-term pest suppression without relying solely on chemical control methods.

Major Pests of Pigeon Pea

A. Pod borer (*Helicoverpa armigera*, *Maruca vitrata*)

Pod borers are the most destructive pests in pigeon pea cultivation, with *Helicoverpa armigera* and Maruca vitrata being the principal species. *Helicoverpa armigera* is a polyphagous pest that feeds on flower buds, developing pods, and seeds. The larvae bore into the pods and consume the seeds, often moving from one pod to another, leading to direct loss in grain yield. A single larva is capable of damaging 10 to 30 pods during its development, especially when infestation coincides with the peak flowering and pod formation stages. Yield losses attributed to *Helicoverpa armigera* can range from 20% to 60%, particularly under late-sown conditions or in the absence of timely pest control. Maruca vitrata attacks flower clusters and young pods. The larvae web the floral parts together and feed from within, which not only damages the flowers and pods but also hinders pollination and grain setting. Infestation by Maruca vitrata is more prominent in humid environments, and the damage may reach 30% to 50% in the absence of protective measures.

Pod fly (*Melanagromyza obtusa*)

The pod fly is a significant pest of pigeon pea during the pod development stage. The adult female lays eggs inside green pods, and the maggots feed on developing seeds. Damage is often internal, making it difficult to detect during early stages. Affected pods remain attached to the plant but contain hollowed or discolored seeds. In severe cases, pod fly infestation can affect 40% to 70% of the pods, resulting in shriveled, deformed, or completely destroyed grains. The pest completes several generations in a single season, and its infestation intensifies during prolonged flowering. Fields with continuous cropping of pigeon pea or overlapping sowing are particularly vulnerable to pod fly outbreaks.

Blue butterfly (*Lampides boeticus*)

The blue butterfly, *Lampides boeticus*, is a minor yet persistent pest of pigeon pea, especially in regions with warm, dry weather. The female butterfly lays eggs on flower buds and young pods. Upon hatching, the larvae bore into the pods and consume the developing seeds. Although individual damage is less severe compared to Helicoverpa, its cumulative effect during multiple generations can significantly reduce seed quality. The larvae are difficult to detect due to their cryptic behavior and remain concealed inside pods for most of their life cycle. Yield losses due to *Lampides boeticus* are generally in the range of 5% to 15%, but this may increase under favorable conditions for the pest.

Integrated Pest Management in Pigeon Pea

Sustainable pest management in pigeon pea relies on integrating multiple strategies to minimize economic losses while maintaining ecological balance. The use of trap crops and border crops is an important preventive measure. Planting early-maturing crops like cowpea or short-duration green gram as trap crops around pigeon pea fields helps attract and retain moths of Helicoverpa and Maruca, reducing pest pressure on the main crop. These trap crops can also act as habitat for natural enemies that regulate pest populations.

Use of trap crops and border crops

Marigold and sunflower are effective border crops that attract *Helicoverpa armigera* for egg laying, which can then be monitored or targeted with localized control measures. Trap crops are selected based on their attractiveness to pest species and are planted ahead of the main crop to ensure their availability during the pest's early reproductive phases.

Biological control and neem-based products

Biological control forms the backbone of IPM in pigeon pea. Natural enemies like *Trichogramma chilonis*, which parasitize eggs of Helicoverpa, and larval parasitoids such as *Campoletis Chlorideae* and *Carcelia Illota* play a significant role in suppressing borer populations. Entomopathogenic viruses like Helicoverpa NPV (HaNPV) are used to target early larval instars. Neem-based biopesticides such as neem seed kernel extract (NSKE) and neem oil act as antifeedants, oviposition deterrents, and growth regulators for various pigeon pea pests. These products are safe for pollinators and natural predators and can be applied during early crop stages to suppress pest colonization.

Cultural practices like timely sowing

Adjusting the sowing date helps synchronize crop flowering with periods of low pest activity (Moore *et.al.,* 1987). Early sowing allows the crop to complete its reproductive phase before the peak population of Helicoverpa and Maruca emerges. Crop residues and volunteer plants are also removed to break pest life cycles and reduce carryover populations. Maintaining adequate plant spacing and good aeration minimizes microclimatic conditions that favor Maruca vitrata infestation.

ETL-based insecticide application

Chemical intervention is recommended only when pest populations exceed the established economic threshold levels. For *Helicoverpa armigera*, the threshold is one larva per plant or more than 10% pod damage. For *Maruca vitrata*, treatment is advised when more than 5% of flower clusters are webbed. For pod fly, spraying is initiated when over 15% of pods exhibit signs of internal damage. Insecticides such as emamectin benzoate, spinosad, and flubendiamide are preferred due to their efficacy and safety toward beneficial organisms. All applications should be targeted and based on pest monitoring to avoid unnecessary pesticide exposure and resistance development. Effective implementation of integrated pest management in pigeon pea not only ensures better yield and quality but also reduces environmental risks and input costs. By combining preventive measures, biological control, and precise chemical use, pest pressure can be managed within economic limits, safeguarding the crop throughout its growth cycle.

Pest Complexes in Other Legumes (Green Gram, Black Gram, Lentil, etc.)

A. Whitefly (*Bemisia tabaci*)

Whitefly (*Bemisia tabaci*) is a major pest affecting green gram, black gram, lentil, and other pulse crops. It infests plants by feeding on the undersides of leaves using its piercing-sucking mouthparts. This feeding weakens the plant by removing sap, leading to chlorosis, leaf curling, stunted growth, and reduced flowering. A severe infestation causes early leaf senescence and poor pod formation, especially during the vegetative to reproductive stages. Beyond direct damage, whiteflies serve as efficient vectors of viral diseases such as mungbean yellow mosaic virus (MYMV), which causes significant yield losses. Infected plants exhibit yellow patches on leaves, which spread across the canopy, ultimately suppressing photosynthesis and pod development. In crops like green gram and black gram, MYMV transmitted by *Bemisia tabaci* can reduce yields by 60% to 80% during epidemic conditions. Whitefly populations increase rapidly under dry, warm weather with low wind speed, which aids their dispersal and establishment in legume fields.

B. Aphids and thrips

Aphids such as *Aphis craccivora* infest lentil, green gram, and black gram during the early to mid-growth stages. These small, soft-bodied insects form dense colonies on young shoots, leaves, and flower buds. By extracting phloem sap, they cause leaf curling, reduced plant vigor, and delayed flowering. Aphids also excrete honeydew, which supports the growth of sooty mold and interferes with plant respiration and photosynthesis. Thrips, including Thrips tabaci and *Frankliniella schultzei,* feed by scraping the leaf surface and sucking out cell contents. This results in silvering or bronzing of leaves, distortion of young tissues, and flower shedding. Both pests cause indirect damage as vectors of plant viruses, notably thrips-transmitted tospoviruses. In lentil and mungbean, aphid and thrips infestations during flowering can lead to a 20% to 40% reduction in yield due to impaired reproductive development and poor seed setting.

C. Pod borers and webbers

Pod borers such as *Helicoverpa armigera* and *Maruca vitrata* are significant pests in short-duration legumes. These insects attack the crop during the flowering and pod-filling stages. *Helicoverpa armigera* feeds externally on buds, flowers, and pods, boring into developing grains and causing direct yield losses. A single larva may damage 15 to 25 pods in its lifetime. *Maruca vitrata* larvae form silken webs around flower clusters and pods, feeding internally and preventing effective pollination. Webbing also shelters the larvae from predators and insecticide sprays. Infestation levels above 15% can lead to seed yield reduction of up to 50%, especially in sequentially sown green gram or black gram during extended flowering periods. Webbing pests are particularly difficult to control without timely detection, making monitoring and early intervention essential for minimizing losses.

D. Integrated Pest Management Approaches

Pest management in short-duration legumes requires a multi-pronged strategy that integrates crop monitoring, ecological methods, biological control, and judicious pesticide use. Regular crop monitoring is the foundation of any pest management program. Field surveys, pheromone traps for borers, and sticky traps for whiteflies and aphids help assess pest population trends and detect early infestations. Monitoring allows timely application of control measures before the pest crosses the economic threshold level, thus avoiding unnecessary chemical usage.

1. Crop monitoring and forecasting

Forecasting based on pest surveillance, climatic conditions, and past outbreak records allows for proactive planning. Temperature and humidity data can be used to predict pest emergence windows for whiteflies and thrips. Decision support systems based on field data enhance the effectiveness of interventions by aligning control efforts with pest life cycles and peak periods of vulnerability.

2. Biological control with entomopathogens

Biological agents offer an environmentally safe option for controlling major legume pests. *Beauveria bassiana*, *Metarhizium anisopliae*, and *Verticillium lecanii* are effective entomopathogenic fungi used to suppress populations of aphids, whiteflies, and thrips. Parasitoids like *Trichogramma chilonis* and Braconhebetor target the egg and larval stages of pod borers. Conservation of natural predators such as ladybird beetles, syrphid flies, and spiders through reduced pesticide use supports long-term pest suppression. Field application of NPV (nuclear polyhedrosis virus) specific to Helicoverpa larvae is another biological method with proven effectiveness in pulse crops.

3. Cultural and chemical control methods

Cultural practices such as timely sowing, crop rotation, and removal of infected plant debris help minimize pest buildup (Abbas *et.al.,* 2019). Early sowing reduces the overlap between susceptible crop stages and peak pest activity. Rotating pulses with non-host crops breaks the pest life cycle and lowers the carryover of pest populations. Rogueing of virus-infected plants during the vegetative phase reduces secondary spread. Chemical control is used only when pest populations exceed the economic threshold level. Selective insecticides such as emamectin benzoate, spinosad, and flubendiamide are applied for pod borer control. Neonicotinoids and insect growth regulators like buprofezin are used for sucking pests but only under strict adherence to ETL guidelines. All pesticide applications must be carefully timed and targeted to avoid disrupting natural enemy populations and pollinators. Pest complexes in legumes like green gram, black gram, and lentil pose serious threats to productivity, particularly due to their short growth duration and synchronized flowering stages, which make them highly vulnerable to pest attack. Effective management through integrated approaches not only prevents yield losses but also enhances crop quality and reduces dependency on chemical inputs, leading to more resilient and sustainable pulse production systems.

Comparative Analysis of Pest Complexes

A. Cross-crop occurrence of polyphagous pests

Polyphagous pests are those that feed on multiple host plants across different crop species, often leading to widespread damage in diverse agroecosystems. Among the most notable polyphagous pests are *Helicoverpa armigera*, *Spodoptera frugiperda*, *Aphis craccivora*, and *Bemisia tabaci*. *Helicoverpa armigera* attacks over 180 plant species including chickpea, pigeon pea, lentil, cotton, tomato, and sunflower. This pest's ability to migrate and adapt to different hosts enables it to survive year-round by moving from one crop to another based on seasonal availability. Its occurrence across cereals, pulses, oilseeds, and vegetables complicates control strategies and requires area-wide management approaches. *Spodoptera frugiperda*, originally a pest of maize, has also been reported on sorghum, sugarcane, and rice. Its aggressive feeding behavior and overlapping generations contribute to rapid buildup across regions. *Aphis craccivora*, though primarily associated with legumes, can survive on several weed species and alternate hosts during off-seasons, ensuring its persistence and resurgence. *Bemisia tabaci* affects more than 600 plant species and spreads viral diseases such as mungbean yellow mosaic virus and cotton leaf curl virus, affecting productivity in both pulses and fibre crops. The cross-crop presence of these pests increases the risk of simultaneous outbreaks and limits the effectiveness of crop-specific interventions.

B. Differences in pest incidence between Kharif and Rabi seasons

Pest dynamics vary significantly between Kharif and Rabi seasons due to differences in temperature, humidity, rainfall, and crop phenology. The Kharif season, characterized by higher humidity and frequent rains, favors pests like *Maruca vitrata*, *Melanagromyza obtusa*, and sucking pests including whiteflies and thrips. High relative humidity supports the development of pod webbers and flower feeders, particularly in pigeon pea and green gram. The Rabi season typically presents drier and cooler conditions, which influence the activity of pests like aphids and cutworms. Aphid populations such as *Aphis craccivora* and *Schizaphis graminum* surge during Rabi due to their preference for cool and dry climates, especially in wheat, chickpea, and lentil. Cutworms also thrive under low temperature and moist soil conditions, making early Rabi crops more vulnerable. The timing of pest infestation also varies; *Helicoverpa armigera* causes more damage in Rabi-season chickpea when flowering and pod formation occur during a time of increased moth emergence. Seasonal shifts in crop calendars can alter the pest population dynamics, often resulting in unexpected surges in pest numbers due to asynchronous crop stages and lack of natural enemy activity.

C. Impact of cropping systems and climatic conditions

The structure of cropping systems plays a critical role in shaping pest complexes. Monocropping or continuous cultivation of the same crop in the same field increases the pest burden by creating a stable habitat for host-specific and polyphagous pests. Cropping systems dominated by legumes without adequate rotation encourage buildup of pod borers, aphids, and whiteflies. Intercropping systems with non-host or trap crops can suppress pest incidence by disrupting pest movement and supporting predator populations. For example, intercropping pigeon pea with sorghum has shown reduced incidence of *Helicoverpa armigera* due to altered microclimatic conditions and increased parasitism. Climatic factors such as rainfall pattern, temperature extremes, and wind speed directly influence pest behavior, reproduction, and migration. High temperatures accelerate the development rate of pests like *Spodoptera frugiperda*, leading to more generations within a single cropping season. Unseasonal rains during flowering stages can increase the humidity level, favoring the emergence of webbing pests like *Maruca vitrata*. Drought conditions tend to intensify the problem of sucking pests, especially whiteflies and aphids, due to reduced plant defense and absence of fungal diseases that typically regulate pest populations. Climatic variability also affects the efficacy of biocontrol agents and alters the balance between pests and their natural enemies. Understanding the interaction between pest complexes, seasonal variability, and cropping systems is essential for developing context-specific pest management strategies that are economically viable and ecologically sound.

Challenges in Pest Management in Cereal and Pulse Crops

A. Pesticide resistance and pest resurgence

One of the major challenges in pest management across cereal and pulse crops is the development of resistance to chemical pesticides. Over-reliance on a limited group of insecticides, especially synthetic pyrethroids, organophosphates, and neonicotinoids, has led to the selection of resistant biotypes in several pest species. *Helicoverpa armigera*, a key pest of chickpea, pigeon pea, and lentil, has developed resistance to multiple insecticide classes due to indiscriminate and repeated applications, often without rotation or adherence to threshold-based strategies. Similarly, *Nilaparvata lugens*, the brown planthopper in rice, has shown resistance to buprofezin and imidacloprid in areas with high application frequency. Resistance not only renders chemical control ineffective but also increases production costs due to the need for higher doses or alternative products. Repeated applications may also cause pest resurgence, a condition in which pest populations rebound quickly after pesticide use due to the elimination of natural predators and parasitoids. This resurgence is common in aphids and whiteflies, where natural enemy suppression leads to explosive population growth, compounding the damage and reducing crop yields.

B. Disruption of natural enemy complexes

The excessive and unselective use of broad-spectrum insecticides disrupts ecological balance by destroying beneficial arthropods that naturally regulate pest populations. Parasitoids such as *Trichogramma chilonis*, predators like ladybird beetles (*Coccinella septempunctata*), and spiders contribute significantly to pest suppression in cereal and pulse fields. These natural enemies are highly sensitive to insecticides, especially during larval or nymphal stages. When these organisms are removed from the system, secondary pests that were previously under control can multiply unchecked. In rice ecosystems, reduction in spider populations due to pesticide use has led to higher incidence of leaf folders and planthoppers. In chickpea and pigeon pea, the decline of parasitoids allows higher survival rates of early instars of *Helicoverpa armigera*. The breakdown of predator-prey dynamics increases dependence on chemical control, leading to a vicious cycle of pesticide use and pest resistance.

C. Climate variability and new pest emergence

Changes in climate patterns, particularly temperature fluctuations, altered rainfall distribution, and increased frequency of extreme weather events, have created favorable conditions for the emergence of new pest species and range expansion of existing ones. Warmer temperatures can accelerate insect development, shorten generation time, and lead to more overlapping generations. This phenomenon has been observed in pests like *Spodoptera frugiperda* in maize, where climatic conditions have enabled rapid spread and increased damage intensity. Drier and warmer winters are conducive to aphid proliferation in wheat, chickpea, and lentil, resulting in higher infestations during reproductive stages. Shifts in pest behavior, such as altered feeding habits or synchronization with sensitive crop stages, can also increase crop vulnerability. New pests such as *Tuta absoluta* and *Thrips parvispinus* have recently emerged in some legume ecosystems, and their presence is often linked to climatic anomalies. Erratic weather also disrupts the effectiveness of biological control agents, such as entomopathogenic fungi and parasitoids, whose survival and activity are climate-dependent. This makes pest forecasting less predictable and complicates planning for timely interventions.

D. Constraints in adoption of IPM at farmer level

Despite proven benefits, the large-scale adoption of integrated pest management (IPM) practices remains limited due to various socio-economic and institutional challenges (Dhawan *et.al.,* 2009). Many farmers lack access to training and awareness about IPM principles, including pest identification, economic threshold levels, and safe pesticide use. Inadequate field-level extension services and limited availability of biocontrol agents restrict the implementation of IPM components such as release of parasitoids or use of entomopathogens. In remote or resource-poor regions, timely access to pest monitoring tools, selective insecticides, or resistant seed varieties is often constrained. The preference for immediate and visible pest knockdown provided by chemical insecticides discourages the use of slower but sustainable biological and cultural methods. Market-driven cropping systems that favor high-value monoculture further amplify pest pressure, increasing reliance on pesticides. Financial limitations, lack of crop insurance, and fragmented land holdings also reduce the willingness of farmers to invest in long-term IPM strategies, which require planning and sustained efforts. Addressing these challenges requires coordinated efforts involving research institutions, extension agencies, and policymakers to promote adaptive, knowledge-based pest management strategies. Strengthening farmer education, improving access to biocontrol inputs, and supporting ecological approaches are essential steps toward achieving sustainable pest control in cereal and pulse production systems.

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Chapter 4

Pest Management in Vegetable Crops

Priyanka Handique*[1], Shruti Biradar[2] and Vaishnavi Tathode[3]

[1]*Ph.D. Scholar, Department of Entomology, Assam Agricultural University, Jorhat*

[2]*Ph.D. Scholar, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri*

[3]*Assistant Professor, Department of Entomology, College of Agriculture, Dhule.*

***Corresponding Author Email:** priyanka.handique.adj25@aau.ac.in

Vegetable crops play a crucial role in ensuring both food and nutritional security by providing essential vitamins, minerals, dietary fiber, and antioxidants. Regular consumption of vegetables is associated with improved immunity, reduced risk of chronic diseases, and enhanced physical well-being. Vegetables such as tomato, brinjal, okra, cabbage, cauliflower, and cucurbits contribute significantly to balanced diets and are key components in combating malnutrition. From an economic perspective, vegetables are high-value crops that generate regular income for smallholder and commercial farmers alike. Due to their shorter growth cycles and high market demand, vegetable farming allows for multiple cropping rounds in a year, offering better returns per unit area compared to many staple crops. They are also central to employment generation across the value chain, from production and harvesting to transport and retail marketing. Urban and peri-urban vegetable cultivation has expanded rapidly, linking rural producers with urban consumers and strengthening local economies.

A. Vulnerability of vegetables to insect pest attack

Vegetable crops are particularly susceptible to insect pest infestations due to their tender plant tissues, high nutritional content, and prolonged flowering and fruiting periods (Kunjwal *et.al.,* 2018). This vulnerability is further intensified by the year-round cultivation and overlapping crop cycles, which provide continuous host availability for pest populations. Insect pests such as *Helicoverpa armigera*, *Bemisia tabaci*, *Leucinodes orbonalis*, *Earias vittella*, and *Plutella xylostella* are capable of causing 30% to 80% crop losses if not properly managed. These pests attack different plant parts including leaves, shoots, flowers, and fruits, resulting in reduced photosynthesis, lower fruit quality, and market rejection. Some pests also serve as vectors for viral diseases, which can further devastate crop productivity.

For example, *Bemisia tabaci* transmits tomato leaf curl virus and yellow vein mosaic virus, leading to total crop failure in extreme cases. Frequent pest attacks not only reduce yield but also increase production costs due to repeated pesticide applications and post-harvest handling losses.

B. Need for sustainable pest management approaches

The rising cost of chemical pesticides, increasing pest resistance, environmental contamination, and health risks to consumers and farm workers underscore the urgent need for sustainable pest management in vegetable production. Conventional practices involving indiscriminate pesticide use often result in pest resurgence, pesticide residues on produce, and disruption of beneficial insect populations. Sustainable pest management emphasizes an integrated approach that combines biological control, cultural practices, host plant resistance, and judicious use of pesticides. Integrated Pest Management (IPM) helps maintain pest populations below economic injury levels while preserving ecological balance. Practices such as the use of pheromone traps, release of parasitoids like Trichogramma spp., application of botanical extracts like neem oil, and the selection of pest-tolerant varieties are key components of sustainable pest control. These strategies reduce input costs, improve produce quality, and support environmental and human health. Adoption of such approaches requires strong research-extension linkages, farmer education, and policy support to ensure wider implementation and long-term success in vegetable pest management.

Major Pests of Tomato

A. Fruit borer (*Helicoverpa armigera*)

Helicoverpa armigera is the most destructive insect pest of tomato, causing substantial yield and quality losses during the flowering and fruiting stages. The adult moth lays eggs on leaves, flowers, and developing fruits. After hatching, the larvae feed on tender foliage initially and later bore into fruits, causing direct damage and exposing them to secondary infections. A single larva can destroy up to 8 to 10 fruits during its development. The presence of bore holes plugged with excreta is a typical symptom of infestation. Yield losses due to fruit borer infestation can range from 30% to over 60% in untreated fields. The pest's wide host range, overlapping generations, and resistance to multiple insecticide classes make its control complex and economically significant.

B. Leaf miner (*Liriomyza trifolii*)

Leaf miner larvae feed between the upper and lower surfaces of tomato leaves, creating serpentine mines that reduce photosynthetic area and weaken plant growth. Infestation is more severe during early vegetative and flowering stages, especially under warm, dry conditions. The adult is a small fly that lays eggs just below the leaf surface, and the hatched larvae mine the internal tissue, forming characteristic white or silvery trails. Heavy infestation causes premature leaf drop and poor fruit set. Yield reduction due to leaf miner infestation may reach 20% to 40% under favorable conditions for pest development. Management is difficult due to the protected feeding habit of larvae and the pest's resistance to contact insecticides.

C. Whitefly (*Bemisia tabaci*) – vector of Tomato leaf curl virus

Bemisia tabaci is a highly polyphagous pest that not only feeds on phloem sap but also transmits Tomato Leaf Curl Virus (ToLCV), a serious disease that can wipe out entire tomato fields. Feeding by whiteflies causes leaf curling, chlorosis, and reduced plant vigor. The virus transmission occurs within minutes of feeding and results in severe stunting, puckering of leaves, and poor fruit development. Infected plants may fail to set fruit or produce small, deformed tomatoes with no market value. Infestation typically begins in the nursery stage and continues throughout the crop cycle. Yield losses due to ToLCV transmitted by *Bemisia tabaci* have been recorded as high as 90% in severely affected fields.

D. Aphids (*Myzus persicae*)

Aphids, particularly *Myzus persicae*, colonize young tomato leaves and shoot tips, sucking plant sap and weakening the crop. Infestation leads to curling of leaves, stunting, and distortion of plant parts. Aphids also produce honeydew, which supports the growth of sooty mold and interferes with photosynthesis. Besides direct damage, they are vectors for several viral diseases that reduce fruit quality and market acceptance. Under high infestation levels, fruit yield may decline by 15% to 30%, depending on the growth stage and environmental conditions. Aphid populations multiply rapidly in cool and humid environments and can infest protected as well as open-field tomato crops.

E. Thrips (*Thrips tabaci*)

Thrips are small insects that cause feeding damage on leaves, flowers, and fruit surfaces. Their rasping-sucking mouthparts lead to silvery patches, scarring, and deformation of plant tissues. Thrips tabaci is also a known vector of Tomato Spotted Wilt Virus (TSWV), which severely affects plant growth and fruit development. Infestation at the flowering stage reduces pollination and causes flower drop, ultimately lowering fruit yield. Thrips are most active during dry weather and can complete multiple generations within a single crop cycle. Yield losses due to thrips feeding and virus transmission can range from 10% to 50% depending on pest pressure and stage of infestation.

F. Integrated Pest Management in Tomato

Integrated management of tomato pests involves a combination of monitoring, biological control, botanical applications, and selective use of pesticides based on economic thresholds. Regular field scouting is essential to detect early infestations and identify pest hot spots. Economic threshold levels (ETLs) guide decisions on intervention. Control measures for *Helicoverpa armigera* are recommended when one larva per plant or 5–10% fruit damage is observed. For whiteflies, action is taken when 8 to 10 adults per leaf are detected during early stages.

1. Monitoring and economic threshold levels

Monitoring through visual inspection, pheromone traps for *Helicoverpa armigera*, and yellow sticky traps for whiteflies, aphids, and thrips helps in tracking pest populations (Murtaza *et.al.,* 2019). These tools provide real-time data that inform the timing of control measures and prevent unnecessary pesticide use.

2. Use of pheromone traps and yellow sticky traps

Pheromone traps specifically attract male moths of *Helicoverpa armigera*, reducing mating success and lowering larval populations. Yellow sticky traps are used to attract and trap whiteflies and aphids, especially in nurseries and early vegetative stages. A density of 10–12 traps per acre is effective for monitoring and partial control.

3. Release of biological control agents (e.g., Trichogramma, predatory bugs)

Biological control includes the release of egg parasitoids like *Trichogramma chilonis*, which parasitize Helicoverpa eggs before hatching. Predators such as *Chrysoperla carnea* (green lacewing) and Orius spp. feed on thrips, aphids, and whitefly nymphs. Conservation of natural enemies through reduced pesticide use is critical for maintaining long-term pest suppression.

4. Botanical pesticides (NSKE, neem oil)

Neem Seed Kernel Extract (NSKE) at 5% concentration and neem oil at 2–3% act as antifeedants and growth regulators. They are effective against soft-bodied insects such as aphids, thrips, and whiteflies. These botanicals are safe for pollinators and beneficial insects and can be used in organic production systems.

5. Selective chemical control

When pest populations exceed economic thresholds, insecticides are applied with careful consideration to their spectrum of activity and environmental impact. Products such as emamectin benzoate, flubendiamide, spinosad, and chlorantraniliprole are effective against Helicoverpa with minimal harm to natural enemies. For sucking pests, selective molecules like buprofezin and spiromesifen are preferred to avoid resurgence and resistance. All chemical applications must follow recommended doses and pre-harvest intervals to ensure food safety and minimize residues on the produce. A well-executed IPM program in tomato ensures consistent productivity, high-quality fruits, and reduced pesticide load on the environment. It supports sustainable farming practices while enhancing profitability for growers through improved pest control efficiency and reduced input costs.

Major Pests of Brinjal (Eggplant)

A. Shoot and fruit borer (*Leucinodes orbonalis*)

The shoot and fruit borer, *Leucinodes orbonalis*, is the most serious pest of brinjal, causing substantial economic losses during all stages of plant development. Adult moths lay eggs on the undersides of leaves, tender shoots, flower buds, and young fruits. Upon hatching, larvae bore into the shoots or fruits and feed internally. Infestation in the vegetative phase results in wilting of shoots, reducing plant growth and branching, while larval damage to fruits leads to rotting, discoloration, and deformation. Infested fruits are unmarketable, resulting in both yield and quality losses. A single larva may damage multiple fruits during its development. Under high pest pressure, fruit damage can exceed 60% if left unmanaged. The concealed feeding habit of the larvae inside plant tissues and the continuous cropping of brinjal throughout the year favor the survival and multiplication of this pest.

B. Jassids (*Amrasca biguttula*)

Jassids, or leafhoppers, are small sap-sucking insects that colonize the undersides of brinjal leaves. They damage plants by extracting cell sap, which causes leaf margins to turn yellow and curl upwards, a condition commonly referred to as “hopper burn.” The symptoms begin with pale green spotting and gradually lead to bronzing, scorching, and drying of leaves in severe cases. Jassid infestation reduces the plant's photosynthetic efficiency, delays flowering, and lowers fruit yield. The pest is particularly damaging during early crop growth stages and can cause up to 30% yield loss under favorable conditions for population buildup, such as warm and dry weather.

C. Mites (*Tetranychus urticae*)

The two-spotted spider mite, *Tetranychus urticae*, is a microscopic pest that thrives on the undersides of brinjal leaves, especially during hot and dry periods. Mites feed by piercing plant cells and sucking out their contents, leading to the appearance of tiny yellow or white spots on leaves, known as stippling. As infestation progresses, leaves become bronzed and webbed with fine silk, ultimately leading to leaf desiccation and drop. Severe mite infestation stunts plant growth, reduces flowering, and leads to poor fruit set. Yield reduction due to mite infestation may range from 15% to 35% depending on the severity and duration of attack. Their small size and webbing behavior make detection and control difficult in the early stages.

D. Whitefly (*Bemisia tabaci*)

Bemisia tabaci affects brinjal both as a direct feeder and as a vector of viral diseases. The adults and nymphs suck phloem sap from the undersides of leaves, causing chlorosis, leaf curling, and stunted growth. Whiteflies also secrete honeydew, promoting the growth of sooty mold, which further reduces photosynthesis. Apart from the physiological damage, *Bemisia tabaci* can transmit viruses such as leaf curl, which significantly reduces marketable yield. Whitefly populations build up rapidly in warm, dry weather and can lead to serious outbreaks if not properly monitored. Infestation often starts at the nursery stage and continues throughout the crop cycle. Yield losses from direct feeding and virus transmission can exceed 50% under heavy infestation.

E. Integrated Pest Management in Brinjal

Effective management of brinjal pests relies on an integrated pest management (IPM) strategy that combines monitoring, cultural practices, biological control, and selective pesticide use. The use of sex pheromone traps is a critical component in the management of *Leucinodes orbonalis*. These traps help monitor adult moth populations and can also be used for mass trapping. Installing 20 to 25 traps per hectare significantly reduces mating and lowers egg laying, thereby disrupting the pest's life cycle.

1. Use of sex pheromone traps for borer

Pheromone traps specifically attract male moths, reducing the number of fertilized females and limiting larval emergence. This method also supports early detection of population surges, allowing timely interventions before larval damage begins.

2. Crop sanitation and removal of infested shoots

Sanitation practices such as regular removal and destruction of infested shoots and damaged fruits help reduce the pest load and break the reproductive cycle of *Leucinodes orbonalis*. Field hygiene, including weed control and elimination of alternate hosts, also suppresses other pests like whiteflies and mites.

3. Application of neem-based formulations

Neem-based products such as neem seed kernel extract (NSKE) and neem oil act as antifeedants, oviposition deterrents, and insect growth regulators. Application of 5% NSKE or 2% neem oil at 10- to 12-day intervals has shown significant suppression of jassids, whiteflies, and early instars of shoot and fruit borer. These formulations are environmentally safe and compatible with biological control agents.

4. Release of parasitoids and predators

Biological control is essential for sustainable pest suppression in brinjal. Release of *Trichogramma chilonis*, an egg parasitoid, effectively reduces the emergence of Leucinodes larvae. Predators such as Chrysoperla carnea (green lacewing) feed on jassids and whitefly nymphs. Conservation of natural enemies through reduced use of broad-spectrum insecticides enhances their population and efficacy.

5. Resistant varieties and need-based insecticides

Cultivation of pest-tolerant or resistant brinjal varieties helps reduce pest incidence. Varieties with tougher calyces and hairy leaves are less preferred by borers and jassids. When pest populations cross economic threshold levels, insecticides are applied selectively. Emamectin benzoate, flubendiamide, and spinosad are recommended for *Leucinodes orbonalis*, while buprofezin and pyriproxyfen are used for whiteflies. All chemical applications should follow the threshold-based approach and adhere to pre-harvest intervals to avoid pesticide residues. An integrated pest management approach in brinjal not only reduces pest pressure but also improves yield quality, enhances crop safety, and supports ecological balance. Adoption of this strategy ensures long-term sustainability of brinjal cultivation with minimized environmental and economic risks.

Major Pests of Okra

A. Shoot and fruit borer (*Earias vittella*)

The shoot and fruit borer, *Earias vittella*, is the most damaging pest affecting okra during both vegetative and reproductive stages (Rathore *et.al.,* 2021). The female moth lays eggs on tender shoots, flower buds, and developing fruits. Upon hatching, the larvae bore into the plant tissues, feeding internally and causing characteristic damage. Bored shoots exhibit wilting and reduced branching, while infested fruits become deformed, discolored, and unfit for marketing. In severe infestations, fruit damage can exceed 50%, leading to significant yield loss and economic setback. The concealed feeding habit of larvae inside fruits and shoots makes early detection and control difficult, and continuous cropping of okra creates a favorable environment for pest persistence across seasons.

B. Jassids (*Amrasca biguttula*)

Jassids are sap-sucking insects that primarily attack okra during early vegetative stages. The nymphs and adults feed on the undersides of leaves, causing marginal yellowing, cupping, and in extreme cases, complete desiccation of foliage. This condition, commonly referred to as "hopper burn," severely reduces photosynthetic activity and plant vigour. Yield losses due to jassid infestation can range from 20% to 40%, particularly in hot and dry conditions which favor rapid multiplication.

Continuous exposure to high pest pressure often results in delayed flowering and fewer marketable fruits.

C. Whitefly (*Bemisia tabaci*) – vector of yellow vein mosaic virus

Bemisia tabaci is one of the most notorious pests of okra, not only for its direct sap-sucking damage but also due to its role as the vector of yellow vein mosaic virus (YVMV). Adult whiteflies congregate on the lower leaf surfaces and transmit the virus within a few minutes of feeding. Infected plants exhibit characteristic yellowing of veins, mosaic patterns, and stunted growth. YVMV-affected plants bear fewer and misshapen fruits that are not suitable for sale. In some regions, yield losses due to YVMV have been recorded at 70% to 90% under epidemic conditions. Whitefly populations build up rapidly during warm, dry weather and are capable of multiple overlapping generations, making them difficult to control once established.

D. Aphids and mites

Aphids, primarily *Aphis gossypii*, and spider mites, such as *Tetranychus urticae*, also pose significant threats to okra. Aphids cluster on young shoots and leaves, extracting plant sap and causing curling, yellowing, and stunted growth. Their honeydew excretion promotes sooty mold development, which hampers photosynthesis and affects fruit quality. Spider mites feed by puncturing individual plant cells, resulting in stippling, leaf bronzing, and defoliation. Infestation by these pests reduces fruit size, flowering intensity, and overall productivity. Yield reduction from aphids and mites may vary between 15% to 30%, depending on the crop stage and environmental conditions.

E. Integrated Pest Management in Okra

An integrated pest management approach in okra is essential to mitigate pest pressure and sustain crop health while reducing dependency on chemical insecticides. Preventive and control measures are based on ecological principles and economic thresholds.

1. Use of yellow sticky traps and resistant varieties

Yellow sticky traps are effective tools for monitoring and reducing populations of whiteflies and aphids. Placing 10 to 12 traps per hectare during early crop stages aids in early detection and suppression. Use of resistant or moderately tolerant okra cultivars reduces the incidence of both YVMV and fruit borer. Resistant varieties act as the first line of defense and limit the damage caused by key pests.

2. Timely sowing and crop rotation

Sowing the crop at an optimal time avoids the peak activity period of major pests such as *Earias vittella* and *Bemisia tabaci*. Early planting allows the crop to establish before pest populations reach damaging levels. Crop rotation with non-host crops like cereals breaks pest life cycles and reduces the chances of pest carryover from one season to the next.

3. Spraying of botanical pesticides and biocontrol agents

Neem-based formulations such as 5% neem seed kernel extract (NSKE) or 2% neem oil provide effective control against sucking pests and early instars of borers. These botanicals function as antifeedants and growth inhibitors, offering safe alternatives to synthetic chemicals. Biological control agents including *Trichogramma chilonis* for egg parasitism of borers and predatory insects like Chrysoperla carnea for whiteflies and aphids enhance pest regulation. Conservation and augmentation of natural enemies are critical in maintaining ecological balance in okra fields.

4. ETL-based use of chemical pesticides

Pesticides are recommended only when pest populations exceed established economic threshold levels. Chemical treatment for *Earias vittella* is initiated when 5% fruit damage is observed, and for whiteflies when 8 to 10 adults per leaf are present during early growth stages. Insecticides such as spinosad, emamectin benzoate, and flubendiamide are effective against borers, while buprofezin and pyriproxyfen offer control of whiteflies with minimal impact on beneficial organisms. All chemical applications should be need-based, targeted, and in accordance with safety regulations to minimize residues and protect pollinators. Integrated pest management in okra improves both yield and fruit quality by maintaining pest populations below economic injury levels while safeguarding the environment and human health. A well-implemented IPM strategy ensures sustainable production, reduces input costs, and enhances farmer resilience against pest outbreaks.

Major Pests of Cabbage and Cauliflower

A. Diamondback moth (*Plutella xylostella*)

The diamondback moth (*Plutella xylostella*) is one of the most widespread and damaging pests of cabbage and cauliflower (Gautam *et.al.,* 2018). The adult moth is greyish-brown with distinctive diamond-shaped markings on the wings. Female moths lay eggs on the undersides of leaves, and the larvae feed on leaf tissue, forming irregular holes and skeletonizing the foliage. Feeding by young larvae results in small windowpanes, while older larvae can cause complete defoliation of the plant. Larval infestation reduces photosynthetic capacity and significantly lowers head formation in cabbage and curd development in cauliflower. Yield losses may reach 70% under conditions favorable to pest proliferation. The species exhibits high fecundity and short developmental cycles, completing multiple generations per season. Resistance to several classes of insecticides, including synthetic pyrethroids and organophosphates, has been well-documented, posing serious challenges to chemical control.

B. Cabbage looper (*Trichoplusia ni*)

The cabbage looper, Trichoplusia ni, is a green caterpillar with a characteristic looping movement due to the absence of mid-abdominal prolegs. The larvae feed voraciously on the leaves of cabbage and cauliflower, often creating large ragged holes and reducing marketable yield. Infestation is most severe during the vegetative and early head-formation stages. The pest is active during warm, humid conditions and is capable of overlapping generations. Damage from cabbage loopers not only affects the quantity of the yield but also significantly lowers market quality, making the produce unsuitable for sale. The yield reduction may vary from 25% to 60% depending on infestation timing and severity.

C. Aphids (*Brevicoryne brassicae*)

Aphids, particularly *Brevicoryne brassicae*, are soft-bodied insects that colonize cabbage and cauliflower during cooler months. These pests congregate on the undersides of leaves, stems, and developing heads or curds. They feed by sucking sap, which results in yellowing, leaf curling, and overall stunting of the plant. Aphid feeding also leads to honeydew secretion, promoting the development of black sooty mold that interferes with photosynthesis. The presence of aphid colonies on marketable parts such as heads or curds makes them unfit for sale, even when yield loss is minimal. Severe infestations can result in 30% to 50% reduction in marketable yield, especially in late-sown or poorly managed fields.

D. Cutworms (*Agrotis Ipsilon*)

Cutworms, particularly *Agrotis Ipsilon*, are nocturnal caterpillars that live in the soil and cut off seedlings and young plants at the ground level during nighttime feeding. These pests pose a threat during transplant establishment, often leading to patchy crop stands. Larvae may also feed on lower leaves, creating irregular holes. The most critical period for cutworm activity is during the early crop stages. Losses due to cutworm damage can range from 10% to 40%, depending on soil moisture, tillage practices, and pest density. Their soil-dwelling habit makes them difficult to detect, and damage often appears suddenly and extensively.

E. Flea beetles (*Phyllotreta* spp.)

Flea beetles are small, shiny, dark-colored beetles that feed on the leaves of cruciferous vegetables. They create numerous small, round holes known as shot holes, which reduce photosynthetic area and disfigure the foliage. Adult beetles are highly mobile and can migrate quickly between fields. Damage is most severe during seedling and early vegetative stages, causing poor establishment and retarded growth. Flea beetle feeding can significantly reduce seedling survival and crop vigor, especially when infestations coincide with dry conditions. Although not typically associated with complete crop failure, flea beetle activity can cause up to 25% yield loss by reducing plant stand and growth rate.

F. Integrated Pest Management in Cruciferous Vegetables

Effective pest control in cabbage and cauliflower requires a multi-faceted IPM strategy combining cultural, biological, and chemical methods guided by economic thresholds. One of the most successful techniques is the use of trap crops such as mustard. Mustard acts as an early attractant for *Plutella xylostella* and aphids, drawing pests away from the main crop. Planting two rows of mustard for every 25 rows of cabbage or cauliflower allows for early detection and targeted pest control. Infested mustard plants are periodically removed and destroyed to prevent pest buildup.

1. Use of trap crops (e.g., mustard)

Trap crops reduce pest load on the main crop by diverting pests to more attractive host plants. Mustard is particularly effective in attracting diamondback moths and aphids and can be strategically used to suppress pest populations with minimal input.

2. Monitoring with light traps and pheromone traps

Light traps are used to monitor nocturnal pests such as cutworms and cabbage loopers, providing early warning signals. Pheromone traps help in tracking adult populations of *Plutella xylostella*, enabling timely interventions. These tools not only support pest forecasting but also contribute to mass trapping and population reduction.

3. *Conservation of parasitoids like Cotesia plutellae*

Cotesia plutellae is a larval parasitoid specific to diamondback moths. Conservation and augmentation of this parasitoid in the field significantly reduce larval populations. Avoiding broad-spectrum insecticides and providing floral refuges helps maintain parasitoid activity throughout the cropping period.

4. Spraying of neem-based insecticides and Bt formulations

Botanical insecticides such as neem oil and neem seed kernel extract (NSKE) provide effective control of aphids, flea beetles, and early instars of caterpillars. Neem products act as antifeedants and oviposition deterrents. Bacillus thuringiensis (Bt) formulations are effective biopesticides targeting larval stages of *Plutella xylostella* and Trichoplusia ni, causing gut disruption and mortality. These biopesticides are safe for beneficial organisms and do not leave harmful residues.

5. Chemical control based on ETL

Insecticides are applied based on established economic threshold levels to minimize unnecessary spraying (Bueno *et.al.,* 2013). For diamondback moth, action is taken when one larva per plant or 5% infestation is recorded. Emamectin benzoate, spinosad, and chlorantraniliprole are effective against caterpillar pests. Aphid control is achieved with selective insecticides like imidacloprid or flonicamid, which minimize impact on natural enemies. All chemical applications are carefully timed and restricted to need-based situations to avoid resistance development and environmental contamination. Adopting a robust IPM framework in cabbage and cauliflower enhances productivity, reduces input costs, and ensures food safety. It also promotes ecological sustainability by preserving beneficial organisms and reducing the burden of chemical residues on the environment and human health.

Major Pests of Cucurbits (Bitter Gourd, Bottle Gourd, Cucumber, etc.)

A. Fruit flies (*Bactrocera Cucurbitae*)

Bactrocera Cucurbitae, commonly known as the melon fruit fly, is the most destructive pest affecting cucurbitaceous crops such as bitter gourd, bottle gourd, cucumber, and ridge gourd. The female fly punctures the soft skin of developing fruits to lay eggs, and the maggots that emerge feed internally on the pulp. This internal feeding results in fruit rotting, deformation, and premature dropping. A single female may lay up to 200 eggs during her lifetime, and multiple generations can develop within a cropping season. Infestation rates can exceed 60%, especially during warm and humid conditions. Infested fruits are unmarketable due to tissue degradation and external oozing. Yield loss due to fruit fly attack ranges from 30% to 80% depending on crop variety, pest pressure, and time of infestation.

B. Red pumpkin beetle (*Aulacophora foveicollis*)

The red pumpkin beetle is a serious pest during the seedling and early vegetative stages of cucurbits. Adult beetles feed on leaves, cotyledons, flowers, and tender shoots, creating large irregular holes and reducing the photosynthetic surface. The grubs live in the soil and feed on roots, causing plant wilting and death in young plants. Beetle infestation leads to poor crop establishment, delayed flowering, and stunted growth. The pest is most active during warm, dry periods and is capable of causing up to 40% plant stand reduction in heavily infested fields. Beetle activity is more intense in poorly managed plots and fields with abundant weed hosts.

C. Epilachna beetle (*Henosepilachna vigintioctopunctata*)

The Epilachna beetle is a polyphagous pest that attacks a variety of solanaceous and cucurbitaceous crops. Both larvae and adults feed by scraping the chlorophyll from leaf surfaces, creating typical window-paning symptoms. Prolonged feeding causes leaves to dry out and reduces plant vigour. Severe infestation leads to defoliation, especially during the late vegetative and early reproductive phases. The beetle prefers humid environments and often builds up in areas with continuous host availability. Yield reduction of up to 25% may occur in crops suffering from unchecked Epilachna beetle populations.

D. Leaf miners and aphids

Leaf miners, particularly Liriomyza spp., damage cucurbits by tunneling between the upper and lower surfaces of leaves. This creates serpentine mines that interfere with photosynthesis and weaken plant vitality. Infestation is usually high during warm, dry weather and is most damaging in young plants. Aphids such as *Aphis gossypii* and *Myzus persicae* suck sap from tender leaves and shoots, causing leaf curling, chlorosis, and stunted growth. In addition to direct feeding, aphids secrete honeydew, which supports the growth of sooty mold, reducing leaf function. High aphid populations can lead to poor flowering and fruit set, reducing marketable yield.

E. Whiteflies and thrips

Whiteflies, particularly *Bemisia tabaci*, and thrips like Thrips palmi are frequent pests in cucurbit fields. Whiteflies colonize the undersides of leaves and feed on phloem sap, leading to leaf curling, wilting, and reduced plant vigour. They also transmit viral diseases such as Cucurbit Leaf Curl Virus (CuLCV), which causes distorted leaf growth and drastic yield reduction. Thrips damage the crop by lacerating leaf tissues and feeding on cell sap, resulting in silvering, curling, and necrosis. These pests also act as virus vectors and may cause indirect economic damage by facilitating disease spread. Heavy infestation during flowering and early fruit development stages can reduce yield by 20% to 50%.

F. Integrated Pest Management in Cucurbits

Management of cucurbit pests demands an integrated approach focusing on ecological, biological, and chemical tools that are economically and environmentally sound. Among the most effective methods for fruit fly management is the use of bait traps. These traps, baited with methyl eugenol and a suitable insecticide, attract and kill adult male fruit flies, thereby disrupting mating and reducing future larval infestations. Sanitation through regular collection and destruction of infested fruits also plays a key role in preventing pest buildup.

1. Use of bait traps and sanitation against fruit flies

The strategic placement of bait traps at a density of 25 to 30 per hectare helps reduce fruit fly populations by targeting adult males. Regular removal of infested and fallen fruits prevents larval development and reinfestation. Clean cultivation and destruction of crop residues reduce overwintering sites for both larvae and pupae.

2. Application of neem oil and NSKE

Botanical pesticides like neem oil (2% concentration) and neem seed kernel extract (5%) are effective against soft-bodied pests such as aphids, whiteflies, and early instar larvae of beetles. These products act as antifeedants, repellents, and growth regulators. Their use is safe for pollinators and natural enemies and compatible with organic farming systems. Repeated applications at 10 to 15-day intervals ensure consistent suppression of pest populations.

3. Use of biocontrol agents like parasitoids and entomopathogenic fungi

Biological control agents provide sustainable long-term pest suppression. Parasitoids such as *Trichogramma chilonis* target the eggs of lepidopteran pests, reducing larval emergence. Entomopathogenic fungi like Beauveria bassiana and Metarhizium anisopliae are used to manage whiteflies, thrips, and fruit fly adults. These biocontrol agents are most effective under high humidity and moderate temperatures. Integration of these organisms into the IPM framework reduces pesticide reliance and supports biodiversity in cucurbit ecosystems.

4. Chemical application based on ETL

Chemical insecticides are used only when pest populations exceed economic threshold levels (Keasar *et.al.,* 2023). For fruit flies, treatment is initiated when 5 to 10% of fruits show oviposition marks or larval damage. For sucking pests like whiteflies and aphids, chemical sprays are considered when more than 10 adults per plant or colonies on 20% of plants are observed. Selective insecticides such as emamectin benzoate, chlorantraniliprole, and spinosad are applied for beetles and borers, while buprofezin and flonicamid are used for sucking pests. All applications must follow label recommendations and safety intervals to avoid residues and prevent pest resistance. The implementation of integrated pest management in cucurbit crops leads to improved fruit quality, reduced pesticide load, and higher economic returns. This approach enhances ecosystem resilience and ensures sustainable production of gourds and melons across diverse agro-climatic zones.

Cross-Cutting Management Strategies

A. Role of crop rotation and intercropping

Crop rotation and intercropping serve as fundamental agronomic practices that disrupt pest life cycles, reduce host plant availability, and suppress pest populations naturally. Rotating vegetable crops with non-host cereals or legumes helps to prevent the buildup of soilborne and polyphagous insect pests, such as cutworms, white grubs, and root-feeding beetles. For example, alternating cucurbits with maize or sorghum disrupts the habitat continuity required for pests like *Bactrocera Cucurbitae* to thrive. Intercropping cabbage with mustard or tomato with marigold reduces pest pressure through trap cropping or repellency mechanisms. The presence of non-host or deterrent crops interferes with the visual or olfactory cues used by insect pests for host location, reducing their successful colonization. These strategies also improve habitat for natural enemies, leading to better ecological balance and pest regulation.

B. Importance of resistant and tolerant varieties

The use of pest-resistant and tolerant crop varieties is among the most sustainable strategies for pest management. Resistance mechanisms may be morphological, biochemical, or physiological, reducing the plant's attractiveness or suitability to pests. Brinjal varieties with dense trichomes and hard calyxes are less preferred by *Leucinodes orbonalis*. In okra, certain genotypes exhibit lower susceptibility to jassids due to antixenosis traits, while cabbage hybrids with tight head formation discourage infestation by *Plutella xylostella*. Deployment of such varieties reduces the need for pesticide applications and offers season-long protection, particularly under low to moderate pest pressure. These genetic traits, once stabilized and widely adopted, enhance crop productivity while maintaining environmental safety.

C. Significance of pest surveillance and forecasting

Pest surveillance provides critical data on the occurrence, distribution, and dynamics of pest populations, enabling timely and targeted control measures. Regular field scouting, supported by the use of pheromone traps, light traps, and sticky traps, helps detect early infestations and prevent outbreaks. Surveillance data is often integrated with weather information to develop pest forecasting models, which predict pest emergence and population peaks. Accurate forecasting helps farmers plan interventions in advance and avoid emergency pesticide use. For example, peak activity periods of *Helicoverpa armigera* and *Plutella xylostella* can be anticipated using trap catch data correlated with temperature and humidity. Such models support extension services in issuing pest alerts and advisory recommendations for judicious pesticide use, safeguarding both crop health and economic viability.

D. Integration of mechanical, biological, and chemical tools

Integrated pest management combines multiple strategies to maintain pest populations below economic threshold levels while minimizing ecological disruption. Mechanical methods such as handpicking of larvae, destruction of infested plant parts, and use of light or pheromone traps provide direct, non-chemical control. Biological tools include the conservation and release of natural enemies like parasitoids (Trichogramma, Cotesia) and predators (Chrysoperla, ladybird beetles), as well as microbial biopesticides like Bacillus thuringiensis, Beauveria bassiana, and Metarhizium anisopliae. Chemical control is integrated only when pest levels surpass threshold limits, with emphasis on selective, low-toxicity insecticides that do not harm beneficial organisms. This combination of approaches enhances pest suppression, delays resistance development, and reduces the risk of resurgence, ensuring both efficacy and sustainability.

E. Minimizing pesticide residues and protecting pollinators

Excessive and indiscriminate pesticide application results in harmful residues on vegetables, posing health risks to consumers and affecting export quality standards. Frequent spraying also disrupts pollinator populations, especially bees, which are vital for fruit set in crops such as cucurbits and tomato. To mitigate these risks, it is essential to follow recommended pre-harvest intervals, apply pesticides during early morning or late evening hours, and avoid spraying during flowering stages. Botanical insecticides like neem oil and NSKE, as well as biopesticides, offer safer alternatives with minimal residual effects. Encouraging pollinator-friendly practices, such as planting flowering strips and avoiding broad-spectrum insecticides, promotes ecological services that contribute to higher yields and betterquality produce. The long-term benefits of residue management and pollinator conservation extend beyond individual farms, influencing public health, biodiversity, and market access. Cross-cutting strategies form the backbone of modern pest management by addressing root causes of pest outbreaks and promoting agroecosystem resilience. Their successful implementation requires coordinated efforts involving farmers, researchers, and extension agents, along with supportive policies that incentivize ecological farming practices and sustainable input use.

Challenges in Vegetable Pest Management

A. Pest resistance to insecticides

The continuous and often unregulated use of chemical insecticides has led to the development of resistance in several major vegetable pests. Insecticide resistance occurs when a pest population evolves the ability to survive doses that would normally be lethal, often due to repeated exposure over multiple generations. Notable examples include *Plutella xylostella* (diamondback moth), which has developed resistance to organophosphates, pyrethroids, and even newer molecules such as spinosad and emamectin benzoate. Similarly, *Helicoverpa armigera* populations have shown tolerance to a broad range of contact and systemic insecticides. Resistance reduces the efficacy of chemical control, increases the frequency and dosage of pesticide applications, and ultimately raises production costs. This trend also encourages the use of broad-spectrum insecticides that negatively impact beneficial organisms and increase the risk of pest resurgence.

B. Limited availability of resistant hybrids

Although genetic resistance is a vital component of integrated pest management, the number of commercially available resistant or tolerant vegetable varieties remains limited. For several crops like brinjal, tomato, and cucumber, the development of pest-resistant hybrids has not kept pace with the evolving pest complex and environmental pressures. In cases where resistant lines exist, they often face challenges such as reduced yield potential, poor consumer preference, or lack of adaptability to diverse agro-climatic zones. Limited investment in public breeding programs, inadequate seed dissemination systems, and insufficient collaboration between research institutions and private seed companies have restricted the reach and acceptance of such varieties. As a result, farmers frequently rely on susceptible hybrids, which demand intensive pest control measures.

C. Lack of awareness among farmers on IPM practices

A major constraint in effective pest management is the knowledge gap between available IPM technologies and their practical adoption at the farm level. Many vegetable growers are unaware of key components of integrated pest management, including the importance of economic threshold levels, the role of natural enemies, and the safe use of biopesticides and botanicals. This lack of awareness results in over-reliance on chemical pesticides, often applied prophylactically without monitoring. Farmers may also lack training in identifying pest species, life cycles, or early signs of infestation, which reduces the precision and timeliness of interventions. Extension systems are often overstretched or inadequately resourced to deliver customized pest management advice to diverse farming communities. Language barriers, low literacy levels, and limited access to scientific information further hinder the widespread adoption of IPM.

D. Need for area-wide community-based approaches

Pest management in vegetables is most effective when practiced on a large scale through collective community-based strategies (Wright *et.al.,* 2017). Isolated efforts by individual farmers often fail to control highly mobile pests such as whiteflies, fruit flies, and aphids, which can migrate from untreated to treated areas. Area-wide management ensures uniform adoption of practices like synchronized planting, mass trapping, release of biological control agents, and coordinated pesticide applications. Implementation of such strategies requires strong community engagement, institutional support, and effective coordination among stakeholders. Lack of organized farmer groups, insufficient training on collective action, and absence of shared pest monitoring networks present significant obstacles to the success of community-level IPM.

E. Pest resurgence due to misuse of insecticides

Pest resurgence refers to the rapid increase in pest populations following insecticide application, often due to the elimination of natural enemies that regulate the pest under normal conditions. The misuse of broad-spectrum insecticides, such as repeated use at sublethal doses or application during non-target pest stages, disrupts the ecological balance within cropping systems. Frequent spraying for sucking pests like whiteflies and aphids can lead to a decline in predatory beetles and parasitoid wasps, allowing pest populations to rebound unchecked. Resurgence can also occur when secondary pests, previously of minor concern, emerge as dominant threats after competitor species or their predators are eliminated. This phenomenon leads to a pesticide treadmill, where farmers are forced to use more chemicals with diminishing returns, ultimately increasing production costs and environmental contamination. The challenges associated with vegetable pest management reflect a complex interaction of biological, technological, socio-economic, and institutional factors. Addressing these challenges requires multi-dimensional solutions, including strengthened extension services, investment in resistant variety development, community-based action frameworks, and promotion of ecologically balanced pest control methods. Empowering farmers with knowledge and access to IPM tools is essential to shift current practices towards more sustainable, productive, and resilient vegetable cultivation systems.

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Chapter 5

Insect Pests of Fruit and Plantation Crops

Pramod S Sonawane*[1], Rakesh B. Patil[2] and Hiraman Burbude[3]

[1]*Assistant professor, Department of Zoology, K T H M College Nashik-422002, Maharashtra*

[2]*Department of Zoology, KSKW College, CIDCO Uttamnagar, Nashik*

[3]*PG Student, Department of Zoology KSKW College Cidco, Nashik*

***Corresponding Author Email:** promoshiva111@gmail.com

Fruit and plantation crops form a critical segment of horticulture and play a significant role in enhancing both nutritional security and rural income. Crops such as mango, banana, citrus, guava, coconut, and tea contribute substantially to dietary diversity by supplying essential vitamins, minerals, and antioxidants. Economically, these crops support millions of farming households through domestic markets and international trade. Mangoes and bananas, occupy prominent positions among tropical fruits with large-scale production and high consumer demand. Plantation crops like coconut and tea are integral to agro-based industries and contribute heavily to employment generation and export earnings. Tea alone supports more than two million workers, especially in regions where alternative livelihood options are limited. The long gestation period, high input costs, and perennial nature of these crops make them high-investment ventures, where pest outbreaks can lead to serious financial losses and threaten farm sustainability.

A. Pest vulnerability due to perennial nature and diverse agroclimatic conditions

Perennial fruit and plantation crops are particularly vulnerable to pest infestations due to the extended presence of vegetative and reproductive structures, which provide a continuous supply of food and shelter for pests (Lindell *et.al.,* 2023). The year-round canopy cover and repeated flowering cycles in crops like mango and citrus create favorable microhabitats for sap feeders, borers, and leaf feeders. Plantation crops such as coconut and tea are often grown in monocultures across vast areas, making them susceptible to pest buildup and rapid spread. Different agroclimatic zones support a wide range of insect pests with unique seasonal dynamics. For example, fruit flies thrive in warm and humid conditions, while red spider mites are more dominant during dry seasons. The presence of multiple overlapping pest generations, coupled with continuous host availability, challenges effective control and increases the risk of chronic infestations. The accumulation of residues, plant debris, and alternate hosts within orchards also supports the survival of dormant stages such as pupae, further complicating pest management efforts.

B. Need for long-term and sustainable pest management strategies

Given the biological and economic characteristics of fruit and plantation crops, pest management must adopt a long-term and ecologically sound approach. Conventional practices that rely heavily on synthetic insecticides are often ineffective in perennial systems due to the persistence of pest populations and the development of resistance. For example, repeated application of insecticides for controlling *Plutella xylostella* in cruciferous crops or *Bactrocera dorsalis* in mango orchards has led to widespread resistance, reducing the efficacy of conventional tools. Moreover, indiscriminate pesticide use in plantation ecosystems disrupts natural enemy populations, causes pesticide residues in harvestable produce, and affects the sustainability of export chains. Sustainable strategies must integrate cultural, biological, mechanical, and chemical methods through an Integrated Pest Management (IPM) framework. Emphasis on pest monitoring, habitat manipulation, conservation of natural enemies, and the use of biopesticides ensures ecological balance and long-term control. The perennial nature of these crops makes them ideal candidates for area-wide pest management programs supported by farmer cooperatives, extension networks, and policy interventions that promote environmentally responsible practices.

Major Insect Pests of Mango

A. Mango hopper (Idioscopus spp.) – biology, damage to inflorescence and shoots

Mango hoppers, primarily *Idioscopusclypealis*, *Idioscopusniveosparsus*, and *Amritodusatkinsoni*, are among the most destructive pests of mango, particularly during the flowering and fruit-setting stages. These insects are small, wedge-shaped, and highly mobile, making them efficient feeders and breeders in mango orchards. The adult and nymphal stages suck sap from tender shoots, inflorescences, and young leaves. Feeding results in curling, drying, and shedding of flowers and tender shoots, directly affecting fruit set and yield. The damage is compounded by the excretion of honeydew, which supports the development of sooty mold that blackens the flower panicles and leaf surfaces, reducing photosynthesis. Under favorable warm and humid conditions, hoppers can breed rapidly, with populations peaking during the flowering season. Infestation can result in a 60–80% reduction in fruit set if unmanaged.

B. Fruit fly (*Bactrocera dorsalis*) – oviposition in developing fruits and fruit rotting

Bactrocera dorsalis, commonly known as the oriental fruit fly, poses a serious threat to mango production due to its direct damage to the fruits and its role in limiting export opportunities. Female flies lay eggs under the skin of mature or ripening fruits. The hatched maggots feed internally on the pulp, causing tissue breakdown and internal rotting. Affected fruits often show brown puncture marks on the surface, become soft, and emit a foul odor. As the larvae exit the fruit to pupate in the soil, secondary pathogens invade, accelerating decomposition. Infestation leads to significant post-harvest losses, particularly in high-rainfall or humid environments. Yield losses ranging from 30% to 80% have been reported in unmanaged orchards. The presence of even a single maggot in exported fruits results in rejection in international markets due to quarantine regulations.

C. Stem borer (*Batocera rufomaculata*) – internal boring and wilting of branches

The mango stem borer, *Batocera rufomaculata*, is a large longhorn beetle whose larvae cause extensive internal damage to the trunk and branches of mango trees. Adult beetles lay eggs in cracks or crevices of the bark, especially in older or weakened trees. Upon hatching, larvae bore into the wood, creating long tunnels and galleries as they feed. Their activity disrupts the vascular system of the plant, leading to symptoms such as wilting of branches, gummosis, yellowing of leaves, and branch dieback. Infestation also increases susceptibility to fungal infections and reduces fruit yield due to reduced canopy vigor. Signs of infestation include the presence of frass and oozing sap at entry points. Once established, the borer is difficult to control because of its concealed feeding habits.

D. Mealybug (*Drosicha Mangiferae*) – sap sucking, sooty mold development

The mango mealybug, *Drosicha Mangiferae*, is a severe pest particularly during the flowering and early fruit development stages. Adult females are wingless, oval-bodied, and covered in white wax, while nymphs are mobile and actively feed on all above-ground parts. Both stages suck sap from young shoots, inflorescences, and tender leaves. Infestation causes flower drop, reduced fruit setting, and general decline in plant health. The honeydew excreted by these insects facilitates the growth of black sooty mold, which covers leaves and panicles, hampering photosynthesis and gas exchange. Infestation is most severe in poorly managed orchards with dense canopies and inadequate ground sanitation. Mealybugs overwinter as eggs in soil cracks or at the base of trees, emerging during early spring and multiplying rapidly if unchecked.

E. Integrated pest management approaches in mango orchards

A comprehensive IPM strategy is essential to manage the diverse pest complex in mango orchards and to reduce dependence on chemical pesticides (Kaul *et.al.,* 2009). Cultural practices such as regular pruning, orchard sanitation, and removal of alternate host plants help in reducing pest habitats and suppressing early pest buildup. For mango hoppers, need-based spraying with contact insecticides like carbaryl or systemic ones such as imidacloprid at pre-flowering and flowering stages helps in controlling peak populations. Use of neem oil at 2–3% concentration provides effective control while minimizing impact on pollinators. To manage fruit flies, orchard sanitation is critical. Regular collection and destruction of fallen and infested fruits breaks the life cycle. Bait traps using methyl eugenol mixed with malathion attract and kill adult males, significantly reducing breeding. Use of bioagents like Metarhizium anisopliae in the soil suppresses pupae. For stem borers, mechanical removal of grubs using a wire probe and plugging holes with insecticide-soaked cotton is practiced. Prophylactic swabbing of trunks with chlorpyrifos solution also deters egg-laying.

Management of mealybugs involves deep ploughing around the tree base during winter to expose and destroy eggs. Application of grease bands around the trunk prevents nymphs from crawling up. Sprays of fish oil rosin soap or neem-based formulations are effective against nymphs. Biological control using *Cryptolaemus montrouzieri* beetles is also beneficial in reducing mealybug populations. An integrated approach that emphasizes early monitoring, ecological methods, and rational chemical use ensures sustainable mango production, improved fruit quality, and compliance with safety standards in both domestic and export markets.

Major Insect Pests of Citrus

A. *Citrus psylla* (*Diaphorina citri*) – vector of citrus greening disease

Citrus psylla, *Diaphorina citri*, is considered one of the most serious pests in citrus cultivation due to its role as the primary vector of huanglongbing (HLB), also known as citrus greening disease. The adult psylla is a tiny, brownish insect that rests at an angle on tender shoots, and its nymphs are yellowish-orange with a flattened body. Both stages feed by sucking sap from young leaves and shoots, causing leaf curling, chlorosis, and stunting of growth. The more devastating impact results from transmission of Candidatus *Liberibacter asiaticus*, the bacterium associated with greening. Infected trees show blotchy mottling on leaves, yellow shoots, poor fruit quality, and eventually tree decline. The disease has no cure and infected trees become non-productive over time. Psylla populations increase rapidly during periods of new flushes, particularly during spring and late summer. Their rapid multiplication, short life cycle, and ability to migrate make them difficult to manage if not addressed at early stages of infestation.

B. Leaf miner (*Phyllocnistis citrella*) – mining in young leaves and reduced photosynthesis

Phyllocnistis citrella, commonly known as the citrus leaf miner, is a pest that targets young flushes of citrus trees. The larva mines between the upper and lower epidermal layers of newly formed leaves, creating serpentine galleries. This mining distorts the leaf, resulting in curling and premature drop. The damage is particularly severe in nursery plants and young orchards, where rapid vegetative growth is essential for tree establishment. By compromising the photosynthetic surface, leaf miners reduce plant vigor and indirectly make citrus trees more vulnerable to pathogens like citrus canker. The adult moths are small, silver-white, and nocturnal, while larval development occurs within 5 to 7 days under warm conditions. Repeated flushes of new growth allow multiple overlapping generations, making the pest active throughout the growing season in suitable climates.

C. Blackfly (*Aleurocanthus woglumi*) – sap sucking and mold formation

The citrus blackfly, *Aleurocanthus woglumi*, is a major pest of citrus causing direct feeding damage and indirect harm through the promotion of sooty mold. Adult flies and their black, spiny nymphs colonize the lower surface of leaves, where they feed on sap and excrete honeydew. The sticky secretions encourage the growth of black mold on leaf surfaces, which interferes with light absorption and gas exchange, ultimately reducing photosynthetic efficiency. Heavy infestation results in yellowing, early leaf fall, and reduced fruit size and quality. Infestation is especially damaging to young trees and orchards located in humid regions. A single female can lay hundreds of eggs, and the pest completes multiple generations per year. The build-up of dense populations during the monsoon and post-monsoon seasons often leads to outbreaks in the absence of timely intervention.

D. Citrus fruit fly (*Bactrocera minax*) – fruit puncturing and larval damage

Bactrocera minax is one of the most destructive fruit flies affecting citrus, especially sweet orange and mandarin. The adult fly lays eggs under the rind of immature fruits. The hatched larvae feed inside the fruit, damaging the pulp and causing internal rotting. Infected fruits often show puncture marks, become discolored, and fall prematurely. Larval feeding results in bitter taste, unmarketable texture, and secondary microbial invasion. This species has a univoltine life cycle, with one generation per year, and pupation occurs in the soil. The fly overwinters in the pupal stage, making soil management practices crucial for its control. Fruit infestation rates can exceed 50% if not managed through timely trapping and sanitation.

E. IPM strategies including biological control, pruning, and selective insecticides

Management of citrus pests requires a multifaceted approach tailored to the biology of each pest and the growth cycle of the citrus tree. For *citrus psylla*, reducing vector population is key to controlling citrus greening. Timely removal of infected branches, coupled with strategic pruning, reduces breeding sites. Natural enemies like *Tamarixia radiata*, a parasitoid wasp of D. citri, have shown significant promise in reducing psylla populations. Insecticide application should be synchronized with flush emergence, using systemic insecticides like imidacloprid or thiamethoxam, based on economic threshold levels. Control of citrus leaf miner focuses on avoiding excessive pruning and nitrogen fertilization, which lead to succulent growth and increased susceptibility. Biological control using parasitoids such as *Ageniaspi citricola* and microbial agents like Bacillus thuringiensis are effective, especially in nurseries. In mature orchards, sprays with neem-based products help suppress larval development with minimal impact on natural enemies.

For blackfly, maintaining canopy ventilation through proper pruning helps reduce infestation. Soap-based insecticides and neem oil disrupt the insect’s waxy cuticle, making them effective against early stages. Predators like Chrysoperla and parasitoids like Encarsia spp. aid in biological suppression. In managing citrus fruit flies, sanitation is crucial. Infested fruits should be collected and destroyed to interrupt the life cycle. Protein bait traps containing malathion and sugar or methyl eugenol-based attractants help in mass trapping adult males. Soil disturbance during the pupal stage, along with the application of entomopathogenic fungi, enhances control. Selective insecticides are used during peak egg-laying periods, with care to avoid harming pollinators and beneficial insects.

Major Insect Pests of Banana

A. Banana weevil (*Cosmopolites sordidus*) – tunneling in pseudostem

Cosmopolites sordidus, commonly referred to as the banana weevil or banana borer, is a significant pest responsible for major yield reductions in banana plantations (Bakaze *et.al.,* 2022). The adult weevil is a dark-colored beetle that remains active mostly during nighttime and hides in the leaf sheath or soil crevices during the day. The female lays eggs in the leaf sheath or at the base of the pseudostem, and the emerging grubs bore into the pseudostem, forming extensive galleries. These tunnels disrupt the vascular system, leading to wilting, reduced nutrient transport, and plant toppling, especially under windy conditions. Infestation levels as low as 10% can result in noticeable yield declines. Heavily infested plants show stunted growth and produce small, malformed bunches. Infestation is more severe in ratoon crops and fields lacking crop rotation or sanitation measures. Since the pest remains hidden during most of its lifecycle, early detection and control are often difficult without regular field monitoring.

B. Banana aphid (*Pentalonia nigronervosa*) – vector of banana bunchy top virus

Pentalonia nigronervosa is a small, soft-bodied aphid that inflicts damage not only through sap sucking but more critically through its role as the primary vector of Banana Bunchy Top Virus (BBTV), one of the most destructive viral diseases in banana cultivation. These aphids colonize the undersides of young leaves and the leaf axils, where they feed on phloem sap. Infested plants exhibit curling and distortion of leaves, marginal chlorosis, and reduced photosynthetic activity. When acting as a BBTV vector, infected plants show distinct symptoms including erect, narrow, and brittle leaves, giving the appearance of a "bunchy top." Disease transmission can occur rapidly due to the aphid's efficient virus retention and dispersal abilities. Once infected, plants become unproductive and must be removed to prevent spread. The aphid reproduces parthenogenetically, leading to explosive population growth under favorable conditions, particularly in warm and humid environments.

C. Thrips (*Thrips flavus*) – fruit scarring and cosmetic damage

Thrips flavus is a slender, yellowish insect that damages banana fruits through its rasping and sucking mouthparts. The pest primarily attacks young, developing banana fingers, causing silvering and corky brown scars on the peel surface. Though the internal fruit quality is typically unaffected, the cosmetic damage significantly reduces market value, particularly for table bananas. High humidity and warm temperatures favor population development, and thrips often build up rapidly during periods of inflorescence emergence and fruit development. Infestation begins with adult females inserting eggs into plant tissues, followed by nymphal stages feeding in concealed locations like the floral bracts and fruit clusters. Since the economic impact is mainly aesthetic, control measures are often overlooked until damage becomes visible, making preventive monitoring essential.

D. Rhizome weevil (*Odoiporus longicollis*) – internal feeding in corm and pseudostem

Odoiporus longicollis, commonly called the banana rhizome weevil, is another major internal borer whose larval stages damage the corm and lower pseudostem. The adult beetle is reddish-brown, and females deposit eggs in cuts or crevices of the pseudostem. The grubs tunnel through the inner tissues, forming galleries that weaken structural integrity, interfere with water and nutrient flow, and increase susceptibility to secondary pathogens. Plants infested with rhizome weevils often display yellowing, wilting, delayed flowering, and low bunch weight. In severe cases, infested suckers fail to establish or collapse before fruiting. The pest remains hidden for much of its life cycle, and infested tissues often show only subtle external signs like small holes with frass extrusion. Yield losses can range from 30% to 70% depending on infestation level and crop stage.

E. Integrated management including sanitation, trapping, and bioagents

Effective management of banana insect pests requires an integrated approach tailored to the pest complex and crop cycle. Sanitation is a foundational practice, involving the removal and destruction of infested pseudostems, old suckers, and plant debris that harbor pests like banana weevil and rhizome weevil. Clean planting material is essential to prevent the introduction of pests and BBTV vectors. Application of neem cake in planting pits acts as a repellent and suppresses soil-dwelling pest stages. Pheromone traps, such as those baited with sordidin for banana weevils, are used for monitoring and mass trapping of adult populations. Trap efficiency is enhanced by placing them in shaded, moist spots near the plant base.

Biological control also plays a key role. Beauveria bassiana and Metarhizium anisopliae are effective entomopathogenic fungi that infect and kill banana weevils and aphids when applied to the pseudostem and soil. Predators like Chrysoperla and parasitoids such as *Aphidius colemani* suppress aphid populations when chemical interventions are minimized. For thrips, timely removal of floral bracts and bagging of bunches reduce oviposition and feeding. Selective insecticides are used based on economic threshold levels, ensuring that natural enemies are conserved. Application of contact insecticides like chlorpyrifos or imidacloprid is reserved for severe outbreaks, particularly in nurseries or early crop stages. Foliar sprays of neem oil or azadirachtin formulations offer control of aphids and thrips with minimal risk of resistance development or residue accumulation.

Major Insect Pests of Guava

A. Fruit fly (*Bactrocera correcta*, *B. zonata*) – infestation leading to fruit drop

Fruit flies, particularly *Bactrocera correcta* and *Bactrocera zonata*, are among the most economically damaging pests of guava. These tephritid flies are known for ovipositing into ripening guava fruits. The female punctures the fruit skin using her ovipositor and deposits eggs beneath the peel. Upon hatching, the larvae bore into the pulp and feed internally, leading to tissue decay and early fruit drop. Infestation results in foul-smelling, discolored fruits that are unfit for marketing or consumption. Yield losses due to fruit fly attacks can exceed 60% under warm, humid conditions favorable for rapid larval development. The lifecycle of the fly allows for multiple generations within a season, with pupation occurring in the soil beneath the trees, ensuring survival across successive harvests. Infestation is particularly high during the rainy and post-rainy seasons when guava fruiting peaks and alternate hosts are abundant.

B. Mealybugs (*Ferrisia virgata*) – sap extraction and growth of sooty mold

Ferrisia virgata, commonly referred to as the striped mealybug, is a major sap-sucking pest that affects guava trees throughout the year, with population surges during dry periods. The nymphs and adult females feed by inserting their stylets into phloem tissues on leaves, shoots, and fruits, withdrawing plant sap and weakening the plant. Heavy infestation results in yellowing, wilting, and premature leaf and fruit drop. The pest excretes a sugary substance called honeydew, which encourages the growth of black sooty mold. The mold interferes with photosynthesis and respiration, further stressing the plant and diminishing fruit quality. The pest often colonizes hidden areas such as leaf axils, branch junctions, and the underside of fruits, making detection and control difficult. Mealybugs also have a mutualistic relationship with ants, which protect them from predators and parasites in exchange for honeydew, exacerbating the infestation.

C. Bark eating caterpillar (*Indarbela tetraonis*) – bark scraping and internal tunneling

Indarbela tetraonis is a wood-boring pest that causes chronic damage to guava trees, especially mature ones. The caterpillar bores into the bark and underlying tissues, forming tunnels and feeding galleries along the trunk and major branches. The larvae remain concealed during daylight and emerge at night to feed on bark tissues. Infestation is indicated by the presence of silken webbing mixed with excreta and chewed plant material at the tunnel openings. Prolonged feeding leads to girdling, which disrupts the transport of water and nutrients, resulting in branch dieback, canopy thinning, and reduced fruit production. Infestation is more severe in dense orchards with poor airflow and unmanaged canopies. This pest is difficult to manage due to its concealed habits and preference for older, less actively monitored trees.

D. Scale insects (*Chloropulvinaria psidii*) – weakening of twigs and branches

Chloropulvinaria psidii, a soft scale insect, causes damage by settling along the midribs and undersides of leaves, as well as on twigs and branches, where it feeds on plant sap (Branco *et.al.,* 2023). Infestation leads to leaf yellowing, premature drop, and overall weakening of the affected branches. Like mealybugs, scale insects secrete honeydew, which encourages sooty mold development, further reducing photosynthetic activity. Heavy infestations result in drying of twigs and, in severe cases, tree decline. These insects reproduce rapidly and produce multiple overlapping generations, making control particularly challenging. Their waxy covering offers protection from contact insecticides, making them less susceptible to conventional chemical control methods.

E. IPM in guava using parasitoids, orchard hygiene, and ETL-based sprays

Integrated pest management in guava focuses on reducing pest incidence through a combination of ecological, cultural, and chemical tools. For fruit flies, orchard sanitation is essential. Regular collection and destruction of fallen and infested fruits prevent larval development and pupation. Soil raking under trees during the pupal stage exposes and kills developing flies. Methyl eugenol traps baited with malathion are used to mass trap male fruit flies, thereby reducing breeding. Bagging of young fruits provides a physical barrier against oviposition and is effective for preventing infestation in high-value orchards. Mealybug populations are managed through the introduction of natural enemies like *Cryptolaemus montrouzieri*, a predatory beetle that feeds on all stages of the pest. Removal of ant colonies using sticky bands or ant baits disrupts their protective relationship with mealybugs and enhances natural enemy effectiveness. Neem oil sprays help suppress nymphal populations with minimal risk to beneficial organisms.

For bark eating caterpillars, early detection is key. Infested areas should be cleaned manually by removing silk and frass, followed by the insertion of a cotton swab soaked in kerosene or dichlorvos into the tunnels and sealing with mud. This practice reduces larval survival and prevents re-entry. Routine inspection of tree trunks and major branches helps in timely intervention before significant damage occurs. Scale insects are suppressed using insecticidal soaps, horticultural oils, and bioagents like *Lecanicillium lecanii*. Spraying should target crawlers, the most vulnerable stage, and be scheduled based on population thresholds determined through field scouting. Light pruning improves airflow and sunlight penetration, reducing conditions favorable to scale build-up and mold growth.

Major Insect Pests of Coconut

A. Rhinoceros beetle (*Oryctes rhinoceros*) – damage to unopened fronds and spears

Oryctes rhinoceros, known as the rhinoceros beetle, is a serious pest that primarily attacks the growing point of coconut palms. Adult beetles are large, dark brown, and equipped with a prominent horn-like structure, which they use to bore into the crown region. The insect prefers to feed on unopened fronds and the soft tissues of the central spindle, creating V-shaped cuts or holes on emerging leaves. Damage is visible when the fronds unfurl, revealing characteristic chewed edges and geometric holes. In severe cases, beetle feeding can destroy the growing point, resulting in arrested growth or palm mortality. Adult beetles breed in organic debris, manure pits, and decaying logs, where larvae develop on decomposing matter. Continuous breeding and overlapping generations make population control difficult without strategic intervention. Damage is most noticeable during monsoon seasons when humidity supports active breeding and adult emergence.

B. Red palm weevil (*Rhynchophorus ferrugineus*) – internal boring and crown damage

Rhynchophorus ferrugineus, the red palm weevil, is considered the most destructive pest of coconut due to its cryptic internal feeding habit and high reproductive potential. Adult weevils are reddish-brown with a long snout and strong mandibles adapted for boring. Females lay eggs in wounds or soft tissues of the palm, and the hatched larvae tunnel into the crown, stem base, or leaf axils. Larval feeding causes extensive internal damage, disrupting the vascular tissue and weakening the palm structure. Early symptoms include yellowing of inner leaves, oozing of brown fluid, and a foul odor near the crown. In advanced stages, the central spindle may collapse, and the palm dies if the infestation is unchecked. The larval stage, lasting up to two months, is the most destructive, and its concealed nature delays detection. Infestation is often facilitated by poor agronomic practices such as unclean pruning or injuries from climbing devices.

C. Black-headed caterpillar (*Opisina arenosella*) – feeding on lower leaf surface

The black-headed caterpillar, *Opisina arenosella*, targets the photosynthetic tissue of coconut palms, causing significant defoliation. Female moths lay eggs on the underside of mature fronds, and the larvae, upon hatching, feed on the green chlorophyll-rich tissue between leaf veins, leaving behind a fibrous skeleton. Damage begins from the lower canopy and progresses upward if unchecked. Infested fronds exhibit a scorched appearance and lose photosynthetic capability, reducing nut yield and palm vigor. The pest can complete several generations in a year, with population peaks during dry, warm conditions. The caterpillars live under silken webs that protect them from natural enemies and insecticidal sprays. Extensive leaf loss can significantly impact the productivity of bearing palms and delay recovery in young plantations.

D. Coconut mite (*Aceria guerreronis*) – damage to young nuts

Aceria guerreronis, commonly known as the coconut eriophyid mite, is a microscopic pest that infests the surface of developing nuts. Mites colonize the narrow space beneath the perianth of tender nuts within two to three weeks of nut set. Feeding activity results in brownish patches and fissures on the nut surface, followed by hardened scabs and malformed husks. Infestation leads to reduced nut weight, poor copra quality, and in severe cases, premature nut fall. The pest spreads rapidly across plantations via wind or through infested planting material. Its small size and concealed habitat make early detection difficult, often leading to unnoticed spread until damage becomes commercially significant. Economic losses in heavily infested orchards can range between 30% to 50% of total yield.

E. Management practices with cultural, mechanical, and biological tools

Integrated management of coconut pests relies on a combination of sanitation, monitoring, mechanical removal, biological control, and need-based chemical intervention. For *Oryctes rhinoceros*, field sanitation is essential. Removal of decaying organic matter, composting of farm waste, and treatment of breeding sites with Metarhizium anisopliae spores reduce larval populations. Mechanical removal of beetles from the crown using iron hooks and installation of pheromone traps containing ethyl-4-methyl-octanoate helps reduce adult beetle numbers.

Management of *Rhynchophorus ferrugineus* includes routine surveillance for early symptoms and destruction of infested palms to prevent spread. Pheromone traps baited with ferrolure attract and trap adult weevils. Injecting systemic insecticides like monocrotophos or neem oil into feeding holes, followed by sealing with mud, helps kill internal larvae. Maintaining clean pruning practices and avoiding injuries during harvesting operations also reduces the risk of egg-laying by female weevils. *Opisina arenosella* control involves cutting and burning heavily infested leaves and promoting natural enemies. Parasitoids like *Goniozusnephantidis*, *Bracon brevicornis*, and *Elasmusnephantidis* are released during early infestation to suppress larval populations. Insecticidal sprays with Bacillus thuringiensis formulations or neem-based products are effective when applied on the lower leaf surface.

Control of *Aceria guerreronis* includes spraying neem oil or azadirachtin formulations mixed with lime-sulphur paste around the nut surface at regular intervals during the fruit development phase. Biological agents such as predatory mites and fungal pathogens like *Hirsutella thompsonii* are being explored for large-scale use. Application of sulfur-based acaricides may be required under severe infestation, ensuring pre-harvest intervals are maintained to avoid residue issues.

Major Insect Pests of Tea Plantations

A. Tea mosquito bug (*Helopeltis theivora*) – feeding on young shoots and leaves

Helopeltis theivora, commonly known as the tea mosquito bug, is a major sap-sucking pest affecting tea plantations, particularly during the flush period when tender shoots and young leaves are abundant. Adult bugs are slender and reddish-brown with long antennae and legs, and they are easily recognized by a characteristic black spot on their thorax. Nymphs and adults pierce plant tissues using their needle-like mouthparts and feed on cell sap. Feeding causes brownish necrotic lesions, which later enlarge and result in the drying and curling of leaf margins. Buds and shoots affected by repeated feeding fail to develop, reducing plucking points and significantly lowering yield. Severe infestation during peak flush periods can result in yield reductions of 20–40%. The bug is active during warm and humid weather, with population peaks during post-monsoon months.

Eggs are inserted into plant tissues, making early detection difficult until visual symptoms appear.

B. Tea thrips (*Scirtothrips dorsalis*) – leaf curling and silvering

Scirtothrips dorsalis is a microscopic insect that attacks the soft, young tissues of tea bushes (Kumar *et.al.,* 2013). Thrips are slender and pale-yellow to brown in color, and their rasping-sucking mouthparts damage the epidermis of young leaves and buds. Feeding activity causes silvering of the upper leaf surface, followed by curling and brittleness. In heavy infestations, leaves may show brown margins and drop prematurely. Damage occurs most frequently in rain-shadow regions and is exacerbated during dry, hot periods when the pest multiplies rapidly. Although small in size, thrips can cause significant economic loss by reducing the quality and quantity of harvestable shoots. Their mobility and ability to colonize within folded leaves and buds make them difficult to detect during early infestation, requiring close field surveillance.

C. Red spider mite (*Oligonychus coffeae*) – defoliation and leaf bronzing

Oligonychus coffeae, the red spider mite, is a common pest across tea-growing regions, particularly under dry and dusty conditions. These mites are tiny, reddish-brown arachnids that reside on the undersides of mature leaves. They puncture plant cells and suck out their contents, resulting in the appearance of minute yellow spots. As feeding continues, affected areas turn bronze and eventually brown, leading to leaf desiccation and drop. Chronic infestation reduces photosynthetic capacity, weakens plants, and decreases the number of productive plucking points. Dusty conditions on plantation roads and prolonged dry spells are ideal for rapid mite multiplication. Mite populations can complete multiple generations in a short period, especially under warm, dry conditions. The pest becomes more problematic in monocropped, poorly irrigated, or mechanically disturbed plantations where natural predators are absent.

D. Shot hole borer (*Xyleborus* spp.) – tunneling in stems

Shot hole borers belonging to the genus Xyleborus are internal stem borers that affect the health and longevity of tea bushes, particularly older ones. Adult females bore entry holes into the woody stems or collar region of tea plants and create extensive galleries where they lay eggs. The larvae and adults feed on symbiotic fungi cultivated within these galleries, rather than directly on the plant tissue. Despite this indirect feeding, the boring activity damages the plant’s vascular system, leading to poor nutrient and water conduction. Infested bushes show wilting, branch dieback, and gradual plant decline. Boreholes are usually visible near the base of the main stems and exude fine, whitish frass. Severe attacks necessitate uprooting of entire bushes. The pest is favored by poor drainage, excessive shade, and abandoned or neglected tea sections, where natural decay provides ideal breeding sites.

E. IPM in tea using acaricides, natural predators, and agroforestry integration

Integrated pest management in tea plantations emphasizes ecological balance and long-term sustainability. Regular monitoring of pest populations and damage thresholds allows for timely and targeted interventions. For *Helopeltis theivora*, early pruning and shade management reduce pest shelter, while neem-based formulations and entomopathogenic fungi such as Beauveria bassiana provide effective biological suppression. Use of botanical extracts and need-based application of insecticides like imidacloprid or lambda-cyhalothrin is recommended only when economic thresholds are exceeded.

In managing thrips, practices such as maintaining adequate canopy humidity, mulching, and minimizing dust accumulation help suppress pest activity. Sprays of neem oil or spinosad, applied during early infestation stages, reduce population build-up. Avoidance of excessive nitrogen fertilizer also lowers the risk of tender foliage that attracts thrips. Control of red spider mites involves reducing dust and dry conditions through improved irrigation and regular washing of bushes. Acaricides such as dicofol or wettable sulfur are applied based on threshold levels, while biological options like *Hirsutella thompsonii* and predatory mites such as *Amblyseius ovalis* are used to maintain natural control. Application intervals are adjusted based on weather and population dynamics. Management of Xyleborus spp. includes removal and destruction of infested bushes, along with improving soil drainage and reducing over-shading to discourage fungal growth. Use of biological agents like entomopathogenic fungi and maintaining tree diversity in surrounding landscapes through agroforestry systems improves natural regulation. Incorporating shade trees such as *Albizia* and *Grevillea* also supports predator and parasitoid diversity, contributing to pest suppression.

Comparative Pest Dynamics in Fruit vs. Plantation Crops

A. Perennial crop challenges: continuous host availability and complex pest cycles

Fruit and plantation crops share the common characteristic of perennial growth, which presents unique challenges in pest management. Unlike seasonal crops that allow for off-season breaks disrupting pest life cycles, perennial systems provide year-round availability of host tissues in the form of leaves, stems, flowers, and fruits. This uninterrupted presence of food and shelter supports the persistence of pest populations across seasons, enabling multiple overlapping generations. Pests such as *Helopeltis theivora* in tea, *Bactrocera dorsalis* in mango, and *Rhynchophorus ferrugineus* in coconut exploit these continuous habitats, often surviving unnoticed until damage becomes economically significant. The absence of a dormancy period for the crop means there is no natural reset in pest pressure, making it essential for farmers to monitor and manage pests continuously. Pest cycles in perennial crops are also more complex due to interactions with pruning schedules, crop phenology, and microclimatic variations across tree canopies and plantation rows.

B. Differences in pest incidence, seasonality, and management intensity

Pest incidence and seasonal dynamics vary considerably between fruit orchards and plantation systems. In fruit crops such as guava and citrus, pest infestations often peak around flowering and fruiting periods, correlating directly with flushes of tender tissues. For example, citrus psylla and fruit flies show marked population increases during spring and monsoon seasons when fresh vegetative growth and fruit development provide suitable feeding and breeding conditions. Plantation crops like coconut and tea experience more uniform pest pressures due to their large canopy structure and extended harvesting windows. Pests such as red spider mites and black-headed caterpillars in tea or eriophyid mites in coconut tend to exhibit prolonged activity, requiring consistent surveillance and multi-stage interventions. Management intensity is also generally higher in plantations due to the scale of cultivation and the economic implications of perennial crop failure. Pests in plantation crops are often internal or concealed feeders, like stem borers and tunnelers, which require specialized detection and control measures. Many fruit pests are external feeders or sap suckers, more readily detected through visual inspection and more responsive to foliar sprays. This difference necessitates varied pest management infrastructure, from pheromone traps and biological control releases to systemic applications and cultural practices tailored to each crop's biology.

C. Role of monoculture vs. mixed cropping in pest buildup

Monoculture practices in both fruit and plantation systems often lead to an increased risk of pest outbreaks due to the uniform availability of host plants over a large area (Altieri *et.al.,* 1984). The absence of crop diversity encourages rapid pest reproduction and spread, especially for host-specific pests like *Odoiporus longicollis* in banana or *Opisina arenosella in* coconut. In such settings, natural enemies find it difficult to thrive due to a lack of alternative prey or habitats, leading to an ecological imbalance. Monocultures also simplify pest movement and reduce barriers to infestation. Mixed cropping or intercropping systems help disrupt pest life cycles and slow their spread by introducing crop heterogeneity. Integrating leguminous cover crops or flowering plants in orchards supports beneficial insect populations that act as natural enemies. In tea plantations, incorporating shade trees not only modifies the microclimate to reduce mite and thrips populations but also enhances biodiversity that stabilizes pest-predator dynamics. Diversified systems create a more complex environment where pests face greater challenges in locating their preferred hosts and surviving in the presence of antagonistic organisms.

Area-Wide Management and Surveillance

A. Importance of coordinated orchard-level pest control

Area-wide pest management involves the implementation of pest control measures across entire agro-ecological zones or contiguous plantations rather than individual farms. This collective approach is critical for perennial fruit and plantation crops, where pest species often have high mobility and affect large geographical areas. Pests like *Bactrocera dorsalis*, *Rhynchophorus ferrugineus*, and *Helopeltis theivora* can travel across multiple farms, rendering isolated pest control efforts ineffective. Coordinated control at the orchard or regional level helps reduce reinfestation, synchronizes management actions such as pruning, trapping, and biocontrol release, and improves overall pest suppression. This strategy also enhances the cost-effectiveness of interventions by leveraging shared resources such as pheromone dispensers, bioagent production units, and spraying equipment. Area-wide approaches are especially effective in breaking pest cycles, minimizing chemical resistance, and sustaining natural enemy populations. The effectiveness of this method relies on the collective participation of growers, local authorities, cooperatives, and technical agencies.

B. Pest monitoring tools: traps, scouting, and forecasting

Successful area-wide management depends on accurate and timely pest surveillance. Monitoring tools such as pheromone traps, yellow sticky traps, light traps, and bait traps are essential for detecting and estimating the population levels of key pests. Pheromone traps, for example, are widely used for *Oryctes rhinoceros*, *Helicoverpa armigera*, and *Leucinodes orbonalis*, allowing growers to make informed decisions about intervention timing. Regular field scouting complements trapping by enabling the visual assessment of pest symptoms such as leaf bronzing, fruit blemishes, boreholes, or pest residues like webbing and frass. Scouting follows a systematic sampling method, often involving a set number of plants per acre and inspection of specific canopy levels or plant parts. Forecasting models that integrate climatic data, pest biology, and historical infestation records enhance early warning systems, allowing for the implementation of preventive measures before pest populations reach damaging thresholds. These models are particularly valuable for predicting the emergence of pests like red spider mites during dry spells or fruit fly peaks in humid conditions.

C. Role of Farmer Field Schools (FFS) and extension services

The success of area-wide surveillance and management largely depends on farmer education and engagement. Farmer Field Schools (FFS) serve as a participatory training platform where growers learn to identify pests and beneficial insects, understand pest thresholds, and adopt IPM practices based on local conditions. Through field-based experiments and peer-to-peer learning, FFS helps build the capacity of growers to interpret monitoring data and apply need-based interventions. Extension services play a pivotal role in organizing FFS sessions, distributing pest advisories, and facilitating access to eco-friendly inputs such as biopesticides and parasitoids. These services also aid in collecting pest incidence data, guiding pest control calendar development, and coordinating mass activities such as synchronized sanitation or bioagent releases. Real-time mobile alerts, printed pest bulletins, and community radio updates further strengthen communication between researchers, extension agents, and farming communities. The combination of technical training and real-time support enhances decision-making at the farm level and ensures consistency in pest control actions across the landscape.

Future and Research

A. Development of pest-resistant varieties in fruit and plantation crops

The development of pest-resistant varieties represents a sustainable and long-term solution to managing economically damaging pests in fruit and plantation crops. Traditional breeding programs, supported by molecular techniques such as marker-assisted selection, have made it possible to identify and incorporate resistance traits from wild relatives and landraces. In crops like guava, significant progress has been made in identifying tolerance to fruit fly (Bactrocera spp.), while in banana, resistance to weevil borers and aphids is being explored through genomic selection. Tea cultivars are under evaluation for resistance to red spider mite and blister blight, offering dual protection against biotic stress. Coconut hybrids have been screened for reduced susceptibility to rhinoceros beetle and eriophyid mite, based on morphological traits such as tougher leaf bases or compact canopy structure that limit pest establishment. The use of CRISPR-Cas9 and transgenic approaches is also gaining attention in pre-commercial trials for introducing resistance genes in perennial crops. The integration of resistant varieties into pest management programs reduces reliance on chemical pesticides and provides resilience under variable climatic and pest pressure conditions.

B. Innovations in bio-intensive IPM and use of drones in orchards

Bio-intensive integrated pest management (IPM) focuses on ecological principles to suppress pest populations using natural enemies, botanicals, habitat management, and non-chemical techniques. Advancements in microbial biopesticides, such as entomopathogenic fungi (Metarhizium anisopliae, Beauveria bassiana) and virus-based formulations (NPV), have shown significant potential in managing pests like *Helicoverpa armigera*, tea mosquito bug, and coconut rhinoceros beetle. These options are being enhanced through microencapsulation and UV-protection technologies to increase shelf life and field efficacy. Drone-based applications are emerging as a transformative tool in precision pest management. Unmanned aerial vehicles (UAVs) equipped with multispectral sensors can detect early-stage pest infestations by analyzing leaf chlorophyll levels, canopy temperature, or pest-specific damage patterns. Drones can also apply biopesticides, pheromone formulations, or spot-spray insecticides with high precision, minimizing input costs and reducing drift to non-target organisms. Automation in orchard surveillance and targeted interventions using AI-integrated drones allows for rapid response and data-driven decision-making, especially in large-scale plantations where manual monitoring is labor-intensive and time-consuming.

C. Policy support for eco-friendly pest management and export compliance

The expansion of global markets for fruit and plantation produce demands strict compliance with international phytosanitary standards and residue limits (Lengai *et.al.,* 2022). National and regional policy frameworks play a crucial role in enabling farmers to meet these standards through structured programs that support eco-friendly pest management. Subsidies for biopesticides, incentives for adopting IPM practices, and inclusion of natural enemy rearing under rural employment schemes are essential mechanisms that strengthen adoption at the grassroots level. Certification programs such as GlobalG.A.P. and Organic Certification require verifiable pest management protocols that prioritize non-chemical methods, making it essential for growers to align their practices with export market expectations. Regulatory support for timely approval and quality control of biological control products, along with investment in local bioagent production infrastructure, ensures consistent supply and reliability. Extension networks must be equipped to train growers on low-residue practices, pesticide rotation schedules, and recordkeeping needed for traceability. Future research must focus on risk assessment of emerging pest threats under climate change scenarios, resistance management strategies, and the socio-economic impacts of adopting advanced IPM technologies across diverse cropping systems.

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Chapter 6

Pest Management in Spices, Condiments, and Ornamental Plants

S. Pushpatha*[1], D. Nagaraju[2] and B. Sravanthi[3]

[1]*Department of entomology, Faculty of agriculture, Annamalai university, Annamalai Nagar*

[2]*Associate Professor and Head Department of Botany, Government City College (A) Nayapul, Hyderabad, Telengana, 500072*

[3]*Research scholar, Department of Botany, Osmania University, Hyderabad*

***Corresponding Author Email:** mgjayaprakash22@gmail.com

Spices, condiments, and ornamental crops occupy a vital niche in agricultural systems due to their commercial, culinary, and cultural significance. Spices like chilli, turmeric, coriander, and cumin are major contributors to the global spice trade, supplying both domestic consumption and export markets. India alone contributes over 75% of the global turmeric production and is among the leading exporters of chilli and coriander. Spices are not only flavoring agents but are also valued for their medicinal and preservative properties. Condiments serve essential roles in food processing and herbal formulations. Ornamental crops such as rose, jasmine, gladiolus, and chrysanthemum generate substantial income through the floriculture sector, particularly in urban and peri-urban horticulture. Flowers are marketed for fresh decoration, perfumes, garlands, and religious purposes. The aesthetic and aromatic appeal of ornamentals combined with the therapeutic and economic importance of spices ensures that these crops remain high-priority sectors for agricultural development and value addition.

A. Sensitivity of these crops to insect pests due to high value and export potential

High-value crops like spices and ornamentals are extremely sensitive to insect pest damage, both in terms of quantitative yield and qualitative parameters (Das *et.al.,* 2018). Even minimal pest infestation in flower crops can drastically reduce market acceptance due to the cosmetic sensitivity of buyers. In export consignments, pest presence or chemical residue beyond permissible limits often results in consignment rejection and loss of market access. Crops like chilli are susceptible to multiple pests including thrips, mites, and fruit borers, all of which affect the final produce quality. Turmeric and coriander suffer from soil-borne insects and sap feeders that affect rhizome formation and seed setting respectively. Pest outbreaks in jasmine and rose can lead to flower drop, color fading, or deformation, reducing both yield and commercial value. The short harvesting window and delicate nature of these crops demand timely and effective pest control measures that do not compromise quality or safety.

B. Importance of aesthetic value in ornamentals and quality in spices

In ornamental crops, the visual appeal is the single most critical market determinant. Insects such as aphids, mites, and thrips can cause disfigurement, petal damage, or leaf curling, directly impacting their saleability. Even minor spotting or bronzing on petals can render an ornamental flower unsellable in the retail market. The floriculture industry is also linked to the hospitality and event sectors, which require flawless blooms throughout the year. On the other hand, spice quality is measured through essential oil content, color, aroma, and cleanliness—all of which are negatively affected by insect activity. For example, thrips damage in chilli leads to deformed pods and reduced capsaicin content. Rhizome scales in turmeric can lower curcumin content and cause internal decay. The quality of these crops is tightly linked to their price in both domestic and export markets, making pest management a key component in ensuring economic returns and food safety standards.

C. Objectives of pest management in high-value crops

The core objectives of pest management in spices, condiments, and ornamentals revolve around minimizing economic losses, preserving quality, ensuring residue compliance, and protecting ecological balance. The aim is to prevent pest outbreaks through early detection and timely intervention using eco-friendly tools. Long-term strategies include promoting natural enemies, using botanical pesticides, and implementing cultural practices that disrupt pest life cycles. Precision in pest control is essential to reduce crop damage while minimizing input costs and environmental risk. Another important goal is to reduce pesticide residues to meet global food safety standards and ensure market competitiveness. Pest management in these crops must also support sustainability by conserving pollinators and reducing chemical loads in agro-ecosystems. Through integrated pest management strategies, farmers can achieve optimal yields with acceptable quality standards while safeguarding both crop health and environmental integrity.

Major Pests of Chilli (Capsicum spp.)

A. Thrips (*Scirtothrips dorsalis*) – leaf curl and stunted growth

Scirtothrips dorsalis, commonly known as chilli thrips, is one of the most damaging pests in chilli cultivation. The adult thrips are minute, slender insects with fringed wings and high mobility, often colonizing the undersides of tender leaves and young shoots. Both nymphs and adults lacerate the leaf surface and feed on plant cell contents using their rasping-sucking mouthparts. Their feeding causes silvery streaks and upward leaf curling. In severe cases, terminal growth is arrested, resulting in dwarf plants with clustered leaves. The pest is particularly destructive during dry, warm weather, and population explosions are often observed when rainfall is scarce. Continuous feeding not only affects vegetative growth but also delays flowering and fruit set, leading to substantial yield losses. In some trials, thrips infestations have led to yield reductions exceeding 30% in untreated fields.

B. Mites (*Polyphagotarsonemus latus*) – bronzing and leaf deformation

The broad mite, Polyphagotarsonemus latus, is another significant pest in chilli that often co-occurs with thrips, compounding the severity of damage. These mites are microscopic and feed on young leaves, buds, and tender fruits. Their feeding injects toxic saliva into the plant tissue, leading to bronzing, crinkling, and blistering of leaves. Affected leaves become distorted and leathery, often resembling virus-infected symptoms. In flowering plants, infestation leads to flower drop and malformed fruits with rough surfaces. Unlike other pests, broad mites prefer humid environments and are commonly seen in dense canopies where airflow is restricted. Their presence is typically confirmed through microscopic examination due to their minute size and hidden feeding behavior. Continuous infestation results in unmarketable fruits and prolonged crop recovery periods.

C. Fruit borer (*Helicoverpa armigera*) – boreholes and fruit rotting

Helicoverpa armigera, also known as the gram pod borer or fruit borer, is a highly polyphagous insect that infests several solanaceous crops, including chilli (Mishra *et.al.,* 2021). Adult females lay eggs on young flower buds or developing fruits. Upon hatching, the larvae bore into the chilli pods, feeding on internal tissues and developing seeds. The external symptom includes round boreholes often plugged with frass. Infestation results in fruit drop, deformation, and secondary infection due to fungal colonization of the wounds. The pest can complete multiple generations in a single season, especially during moderate temperatures. Losses caused by H. armigera in chilli can range from 20% to 60%, depending on the crop stage and population intensity. The pest is notorious for developing resistance to commonly used insecticides, necessitating the integration of alternative control strategies.

D. Aphids (*Myzus persicae*) – virus transmission

Myzus persicae, or green peach aphid, is a major sap-sucking pest of chilli that also acts as an efficient vector of several plant viruses, including Cucumber Mosaic Virus (CMV) and Potato Virus Y (PVY). These soft-bodied insects colonize young shoots and leaf axils, feeding in large numbers and extracting plant sap. Their feeding causes chlorosis, leaf distortion, and wilting under heavy infestation. More significantly, aphids can transmit viruses in a non-persistent manner, meaning even brief probing can result in disease transmission. Virus-infected plants exhibit mottling, stunting, and fruit malformation, which severely affect yield and marketability. Aphids multiply rapidly under mild temperatures and are often facilitated by nitrogen-rich foliage, which promotes their development. Their tendency to shift between hosts during the growing season adds complexity to their management.

E. Integrated pest management strategies

Managing chilli pests requires a combination of cultural, biological, and chemical approaches that are aligned with economic thresholds and ecological safety. The use of resistant or tolerant chilli varieties forms the first line of defense against thrips and mites. Field sanitation, timely removal of infested plant parts, and crop rotation with non-host species help reduce initial inoculum. For thrips and aphids, installing yellow and blue sticky traps at canopy level enables early detection and mass trapping. Biological control plays a central role, with predators such as Chrysoperla carnea (green lacewing), Oriusinsidiosus (minute pirate bug), and parasitoids like *Trichogramma chilonis* targeting eggs and nymphs of key pests. Application of neem-based products, such as neem seed kernel extract (NSKE) and azadirachtin formulations, provides effective control with minimal impact on beneficial fauna. For H. armigera, pheromone traps for adult monitoring and release of Helicoverpa Nuclear Polyhedrosis Virus (HaNPV) are recommended during flowering and fruiting stages. When chemical control is necessary, selective insecticides like spinosad, emamectin benzoate, and flonicamid are preferred to minimize non-target effects. Spraying must follow economic threshold levels (e.g., 5 thrips per leaf, or 10% fruit borer infestation) to ensure rational use of pesticides and delay resistance development.

Major Pests of Turmeric (*Curcuma longa*)

A. Rhizome scale (*Aspidiella hartii*) – shriveling and reduced rhizome quality

The rhizome scale, *Aspidiella hartii*, is a major insect pest that affects the subterranean parts of turmeric, particularly the rhizomes, which are the primary economic product of the crop. These scale insects are small, circular to oval, and covered with a hard, protective shell. They infest the rhizomes directly by sucking plant sap, leading to shriveling, drying, and discoloration. Infested rhizomes show significant weight loss, internal browning, and are rendered unfit for both seed and market purposes. Scales are usually introduced through infected seed material and multiply rapidly in moist and warm soil conditions, particularly when pre-harvest sanitation is neglected. Yield losses due to A. hartii infestation can range from 15% to 30%, depending on the severity and duration of infestation. The pest is difficult to detect during early stages, making it a hidden threat that continues to damage the crop underground until harvesting.

B. Shoot borer (*Conogethes punctiferalis*) – dead heart symptoms

The shoot borer, *Conogethes punctiferalis*, is another serious pest of turmeric, primarily affecting young plants by boring into the central shoots. The adult moth is yellowish with black spots on its wings, and the larvae bore into pseudostems and feed internally. This internal feeding leads to a condition known as "dead heart," where the central leaf dries up and becomes non-functional while the outer leaves remain green. This kind of damage is particularly severe during the early vegetative growth stages. Larval tunneling also weakens plant structure, inhibits photosynthesis, and ultimately reduces rhizome formation. Yield reductions of up to 25% have been recorded in untreated fields heavily infested with C. punctiferalis. Egg-laying is favored by dense canopies and high humidity, making monocropped fields and poorly aerated plots more susceptible to infestation.

C. Leaf roller (*Udaspes folus*) – leaf folding and feeding

Udaspesfolus, commonly referred to as the turmeric leaf roller, is a minor but occasionally damaging pest that targets the foliage of the plant. The adult is a dark brown butterfly, and the larva folds the leaves longitudinally and feeds from within, consuming green tissue and leaving behind only veins and skeletonized leaf surfaces. Affected leaves lose their photosynthetic capacity, which results in overall stunting of plant growth and reduced rhizome development. Infestations are generally localized but can become widespread under favorable weather conditions. Leaf rolling also creates microhabitats that protect the larvae from natural enemies and chemical sprays, complicating control efforts. When unchecked, infestations can affect up to 10–15% of the total foliage area, especially during late monsoon periods.

D. IPM practices including clean planting material, traps, and soil treatments

Integrated pest management in turmeric begins with the selection of healthy, pest-free rhizomes for planting (Roy *et.al.,* 2021). Seed treatment using neem cake or hot water (52°C for 30 minutes) effectively reduces rhizome scale infestations before planting. Field hygiene, including removal of crop residues and alternate host plants, helps suppress shoot borer populations. Light traps are useful for attracting and controlling adult moths of Conogethespunctiferalis, while pheromone traps assist in monitoring their population peaks for timely intervention. Soil application of neem cake at 250 kg/ha enriches the soil and acts as a bio-repellent against soil-borne pests. Biological control using entomopathogenic fungi like Beauveria bassiana or Metarhizium anisopliae shows effectiveness against both rhizome scale and shoot borer. Need-based chemical applications using chlorantraniliprole or emamectin benzoate are considered when economic threshold levels are reached, usually when more than 10% of plants exhibit dead heart or visible scale infestation.

Cultural practices such as crop rotation with non-hosts, proper drainage to avoid soil moisture accumulation, and wider spacing to improve aeration are also essential in reducing pest incidences. A combination of early detection, preventive measures, and environmentally safe control tools ensures long-term suppression of turmeric pests, resulting in improved rhizome yield and quality suitable for both domestic consumption and export markets.

Major Pests of Coriander (*Coriandrum sativum*)

A. Aphids (*Hyadaphis coriandri*) – reduced seed setting and virus spread

The coriander aphid, *Hyadaphis coriandri*, is one of the most significant pests affecting coriander, particularly during the flowering and early seed-setting stages. These soft-bodied insects cluster in large numbers on tender shoots, inflorescences, and undersides of leaves. Both nymphs and adults feed by sucking sap from phloem tissues, leading to curling, yellowing, and premature drying of affected plant parts. Their feeding causes direct physiological stress, reduces flowering intensity, and affects the viability of developing seeds. Aphid infestation can reduce seed yield by 30–50% under heavy population pressure. Beyond direct damage, these aphids serve as vectors for viral pathogens such as the Carrot Motley Dwarf virus, which spreads rapidly through colonies and can compromise crop quality. Their rapid reproduction rate and tendency to shift between hosts make them challenging to manage once established in the field.

B. Cutworms (Agrotis spp.) – seedling damage

Cutworms belonging to the genus Agrotis are soil-dwelling nocturnal caterpillars that inflict substantial damage to coriander seedlings during the early establishment phase. The larvae remain hidden during the day and emerge at night to sever young stems at ground level, often cutting entire rows in patches. Damage typically appears as wilting or fallen seedlings, and the pests continue feeding on foliage and stems if unchecked. Species such as Agrotis Ipsilon are known to cause up to 25% seedling mortality, particularly in dry, sandy soils with poor weed management. These pests are more prevalent in fields with excessive organic debris, unmanaged weeds, and previous legume cultivation. Moist soil conditions after irrigation can also encourage larval emergence and activity. Economic impact arises from the need for re-sowing and poor plant stand, which directly lowers overall yield.

C. Pod borers (*Helicoverpa* spp.) – damage to developing seeds

Pod borers, primarily *Helicoverpa armigera*, target coriander during its reproductive stage, feeding on the developing umbels and immature seeds. Adult moths lay eggs on flower heads or young pods. After hatching, larvae feed voraciously on the floral parts and developing seeds, often webbing the umbels and creating entry points for secondary fungal infections. Affected seeds become shriveled, malformed, or aborted entirely. In severe infestations, yield losses can reach 35%, especially under warm and dry climatic conditions that favor multiple pest generations. The presence of pod borers during critical flowering periods is highly detrimental, as coriander is grown for both seed and essential oil production, and any damage to reproductive parts directly compromises market value and oil yield.

D. Sustainable pest management in seed spice cultivation

Managing pests in coriander requires a holistic approach, emphasizing sustainability due to its use in food, medicine, and exports. Selection of healthy, certified seed ensures the crop begins with minimal pest risk. Crop rotation with non-host cereals and timely sowing avoid peak pest pressure windows. Intercropping coriander with mustard or fenugreek reduces aphid buildup by disrupting host plant continuity and improving natural enemy activity. Installation of yellow sticky traps helps in monitoring aphid flights, while light traps are effective in attracting adult cutworm and pod borer moths. Biological control is crucial, with natural enemies like Aphidius colemani for aphids and *Trichogramma chilonis* for Helicoverpa showing strong field efficacy. Neem-based formulations at 2–3% concentration act as repellents and anti-feedants against soft-bodied insects. Soil treatment with neem cake (150–200 kg/ha) and application of entomopathogenic fungi like Metarhizium anisopliae suppress soil-dwelling pests like cutworms. In case of heavy infestations, selective insecticides such as flonicamid for aphids and emamectin benzoate for pod borers are recommended based on economic threshold levels, which are typically 15 aphids per umbel or 5–8% pod damage. Spray timing must coincide with early larval stages for effective control and to reduce pesticide residue.

Major Pests of Jasmine (Jasminum spp.)

A. Bud worm (*Hendecasis duplifascialis*) – damage to flower buds

The bud worm, *Hendecasis duplifascialis*, is a significant pest affecting jasmine cultivation, particularly in varieties grown for flower harvesting and fragrance extraction (Ashrith *et.al.,* 2020). The adult is a small moth, while the larvae feed on unopened flower buds. Infestation begins when females lay eggs on floral structures, and upon hatching, the caterpillars bore into the buds and consume internal tissues. Affected buds exhibit discoloration, fail to open, and often drop prematurely. In severe infestations, up to 60% of flower buds may be destroyed, directly reducing flower yield and compromising quality for both fresh market and essential oil production. The pest is active throughout the year but reaches peak population levels during warm, humid conditions, especially after rainfall. Larval feeding also causes necrosis and distortion, leaving behind chewed petals and frass that stain remaining blooms and reduce their aesthetic appeal.

B. Web worm (*Nausinoe geometralis*) – webbing and defoliation

Nausinoe geometralis, commonly known as the jasmine web worm, causes extensive defoliation in jasmine plantations. The larvae of this moth exhibit gregarious behavior, producing webbed masses of silk that enclose leaves, shoots, and tender floral parts. Within these webs, larvae feed voraciously on the mesophyll tissue, leaving only the leaf skeleton. This defoliation hampers the plant's photosynthetic efficiency, weakens overall plant vigor, and reduces flowering potential. Heavily infested plants often exhibit delayed or staggered blooming, which affects harvest scheduling and commercial quality. Infestation intensity typically rises during periods of dense foliage growth and high humidity. The overlapping generations of this pest and their web-sheltered habit make them difficult to control with foliar sprays alone.

C. Blossom midge (*Contarinia maculipennis*) – flower bud drop

The blossom midge, *Contarinia maculipennis*, is a tiny fly that causes severe damage to jasmine by attacking developing flower buds. Adult females lay eggs within the buds, and the maggots feed internally on floral tissues. As a result, affected buds fail to open and drop prematurely, leading to substantial reductions in bloom density. External symptoms include browning of the bud tip, necrotic patches, and abnormal swelling. These signs often mimic nutrient deficiencies or physiological disorders, making early detection difficult without close inspection. Yield losses from blossom midge have been recorded at 25–40% under favorable conditions for pest development, especially in poorly ventilated or densely planted gardens. The short lifecycle and hidden larval stage make this pest challenging to manage without preventive strategies.

D. IPM in jasmine for maintaining flower quality and yield

Integrated Pest Management in jasmine focuses on preserving flower yield and maintaining quality standards suitable for market and perfumery use. Cultural practices such as timely pruning and removal of infested buds and shoots reduce the pest carry-over and create an unfavorable microclimate for insect development. Light traps can be deployed to monitor and reduce adult moth populations of *Hendecasis duplifascialis* and *Nausinoe geometralis*. Regular scouting is essential to detect early signs of web formation or bud damage, allowing timely intervention. Biological control agents like *Trichogramma chilonis* are effective in parasitizing the eggs of bud and web worms. Conservation of predators such as lacewings and spiders contributes to natural pest suppression.

Botanical formulations including neem oil (1–2%) and neem seed kernel extract (5%) help deter feeding and oviposition. Soil application of neem cake at flowering can suppress blossom midge emergence by disrupting pupal development. For higher pest loads, selective insecticides like spinosad and emamectin benzoate may be applied based on economic threshold levels (typically one larva per five flower buds or visible webbing on 10% of shoots). Chemical use should prioritize targeted application during early larval stages and follow safety intervals to avoid residue accumulation on market-bound flowers.

Major Pests of Rose (Rosa spp.)

A. Aphids (*Macrosiphum rosae*) – sap feeding and stunted growth

The rose aphid, *Macrosiphum rosae*, is one of the most common and damaging pests affecting rose cultivation. These soft-bodied insects colonize tender shoots, buds, and the undersides of young leaves. Both nymphs and adults feed by piercing plant tissues and extracting sap, which leads to curling, chlorosis, and distortion of leaves. Infestation often begins during early spring and peaks during mild, humid conditions. As aphid populations increase, infested rose plants exhibit reduced shoot elongation, poor bud development, and general stunting. The honeydew excreted by aphids provides a medium for the growth of sooty mold fungi, which blackens leaves and further inhibits photosynthesis. Yield losses in commercial rose fields due to Macrosiphum rosae can reach up to 40% when pest management is delayed, especially in varieties with tender new flushes that favor rapid aphid multiplication.

B. Thrips (*Thrips tabaci*) – petal browning and reduced market value

Thrips tabaci, also known as onion thrips, has adapted to feed on various ornamental plants including roses. Thrips damage is caused by their rasping-sucking mouthparts, which puncture petal cells and extract contents, resulting in silvering, browning, and streaking of petals. The feeding creates small, discolored patches that are particularly visible on light-colored blooms, diminishing their market appeal. Infestation at the bud stage can lead to deformed and underdeveloped flowers. In floriculture units focused on export or retail-grade cut flowers, even minor blemishes caused by thrips make blooms unmarketable. Thrips populations thrive in hot, dry weather and are often introduced through contaminated planting material or nearby host crops. Populations can increase rapidly due to their short generation time, leading to continuous damage throughout the flowering period.

C. Red spider mites (*Tetranychus urticae*) – bronzing and webbing

The red spider mite, *Tetranychus urticae*, is a serious pest in rose cultivation, particularly under protected environments such as polyhouses and greenhouses. These tiny arachnids feed on the undersides of leaves, piercing individual plant cells and extracting contents. Feeding damage causes stippling, yellowing, and eventually bronzing of leaves. Under severe infestations, leaves dry and drop prematurely, resulting in reduced photosynthetic capacity and weakened plant growth. Fine silken webs are often observed on infested leaves and buds, providing a protected environment for mites to reproduce. The pest prefers dry, dusty conditions and thrives in areas with poor air circulation. Yield loss in floriculture units affected by spider mites can exceed 35%, not only through reduced flowering but also due to lowered aesthetic standards required for cut flower marketing.

D. IPM including pruning, resistant cultivars, and bioagents

Integrated pest management in rose cultivation requires continuous monitoring and a combination of cultural, biological, and chemical approaches to maintain flower quality. Pruning of infested shoots and removal of dead leaves help reduce initial pest loads and improve air circulation, making the environment less favorable for aphids and mites. Choosing resistant or tolerant rose cultivars with tougher foliage or reduced trichome density reduces pest colonization. Regular scouting for pests using hand lens or sticky traps allows early detection of thrips and aphids, enabling timely intervention. Predatory insects such as *Chrysoperla carnea* (lacewings) and *Aphidoletesaphidimyza* (aphid midge) play a crucial role in naturally regulating aphid populations, while Phytoseiulus persimilis is effective against *Tetranychus urticae*.

Botanical pesticides like neem oil (2%) and garlic-chili extracts reduce pest pressure while preserving beneficial organisms. For heavy infestations, selective chemical pesticides such as flonicamid for aphids, spinosad for thrips, and abamectin for mites may be applied based on pest density. Chemical sprays should be rotated based on mode of action to prevent resistance buildup and avoid phytotoxicity. Maintaining a clean production environment, managing irrigation to reduce humidity stress, and implementing regular crop rotation with non-host plants strengthen the overall IPM.

Cross-Cutting Pest Management Strategies

A. Importance of nursery hygiene and clean planting stock

Effective pest management begins with preventive action, and one of the most crucial steps is ensuring nursery hygiene and the use of clean, pest-free planting stock (Bradley *et.al.,* 2010). Nurseries serve as primary sources for distributing planting material, and any lapse in sanitation can lead to widespread pest dissemination. Many insects, including aphids, thrips, scales, and mites, can be introduced into fields through infested seedlings or cuttings. Meticulous inspection of nursery beds, proper spacing to enhance airflow, removal of infected plants, and disinfection of tools reduce pest pressure significantly. Soil sterilization through solarization or biofumigation with neem cake suppresses soil-dwelling pests such as cutworms and root grubs. Regular pruning of mother plants, combined with protective netting to prevent vector entry, ensures the propagation of clean material. Clean planting stock enhances early plant establishment, reduces pest load during critical crop growth stages, and minimizes the need for early insecticide use, thus forming the foundation of any sustainable pest management program.

B. Role of botanicals and microbial biopesticides

Botanical pesticides and microbial formulations offer environmentally compatible alternatives to synthetic insecticides in pest control. Neem-based products, such as neem seed kernel extract (NSKE) and azadirachtin, disrupt insect feeding, reproduction, and molting processes across a wide range of pests including aphids, whiteflies, thrips, and caterpillars. Their biodegradability and low toxicity to non-target organisms make them suitable for use in high-value crops like ornamentals and spices. Microbial biopesticides, including Bacillus thuringiensis (Bt), Metarhizium anisopliae, Beauveria bassiana, and Verticillium lecanii, are effective against lepidopteran larvae, sucking pests, and mites. These bioagents infect or intoxicate target pests while preserving beneficial predators and pollinators. Their use is particularly effective under conditions with moderate humidity and when applied during early pest stages. Integration of botanicals and microbial products into pest management programs improves ecological balance, reduces chemical residues, and delays the onset of pesticide resistance.

C. Application of sticky traps and pheromone lures

Monitoring and mass trapping of insect pests using visual and olfactory cues are integral to integrated pest management. Yellow sticky traps are widely employed for monitoring populations of whiteflies, aphids, and thrips, while blue traps are particularly effective against thrips in vegetables and ornamentals. These traps provide early warning of pest buildup and help in assessing the need for control interventions. Pheromone lures, which mimic the sex pheromones of insects, are used to attract male moths of species like *Helicoverpa armigera*, *Earias vittella*, and *Conogethes punctiferalis*. These lures, when placed in delta or funnel traps, allow for population surveillance and also reduce mating success when used in large numbers for mass trapping. Combining pheromone-based tools with light traps helps in managing nocturnal pests and informs the optimal timing of biopesticide or insecticide application. Trap-based techniques are low-cost, non-toxic, and compatible with organic and ecological farming systems.

D. Need-based insecticide use and pollinator safety

While insecticides remain essential tools in pest suppression, their application must be need-based, guided by economic threshold levels (ETLs), and compatible with pollinator safety. Over-reliance or misuse of insecticides leads to resistance development, resurgence of secondary pests, and elimination of natural enemies. ETL-based spraying ensures that insecticides are used only when pest populations cross damaging levels. Selective insecticides, such as flonicamid for aphids or emamectin benzoate for caterpillars, offer targeted action with minimal non-target impact. Spray timing and method also play a key role early morning or late evening applications reduce pollinator exposure, especially in crops like coriander, rose, and jasmine which depend heavily on bees and other insects for pollination. Use of wettable powders, granules, or drip-compatible insecticides lowers drift and contamination. Integrating buffer zones and flowering strips promotes pollinator refuge and contributes to biological control.

Ornamental Crop Protection

A. Residue-free pest management due to aesthetic sensitivity

Ornamental crops, such as roses, chrysanthemums, lilies, and jasmine, demand an exceptionally high level of visual perfection (Santhoshini *et.al.,* 2022). Even minimal blemishes from pest feeding, excreta, or pesticide residues can render entire batches of flowers unsuitable for the premium market. Residue-free pest management becomes essential because visual appeal directly influences economic returns. Consumers and international buyers often reject flowers with visible stains, spots, or chemical traces. Contact insecticides or oil-based sprays can damage delicate petals or alter coloration, making careful selection of pest control methods necessary. Botanical pesticides such as neem oil, which degrade quickly and leave minimal residue, are preferred during the flowering phase. Entomopathogenic fungi like Beauveria bassiana and Verticillium lecanii also play a key role in providing effective pest control while maintaining flower quality. Spray programs must follow strict pre-harvest intervals and be carefully timed to avoid any visible impact on the market-ready product.

B. Impact of environmental factors on pest outbreaks

Pest dynamics in ornamentals are significantly influenced by climatic and micro-environmental conditions. Temperature, relative humidity, rainfall, and air circulation all affect pest population development and activity. High humidity and warm temperatures favor outbreaks of sucking pests like aphids, whiteflies, and mites, especially in crops like jasmine and tuberose. Sudden changes in weather, such as a rise in temperature after rains, can trigger rapid pest multiplication. Protected structures like greenhouses and polyhouses can exacerbate pest buildup due to stable temperatures and limited natural enemy activity. Continuous flowering in ornamentals ensures a constant food source for pests, contributing to multiple overlapping generations and chronic infestations. Understanding local weather patterns, implementing regular monitoring, and adapting pest control timing based on environmental cues are crucial for successful management.

C. Role of protected cultivation in pest exclusion

Protected cultivation using structures such as polyhouses and net houses plays a dual role in ornamental crop protection. These environments provide a physical barrier that restricts the entry of flying insect pests such as thrips, whiteflies, and aphids. Fine mesh insect-proof nets with pore sizes below 40 mesh can block adult pests without restricting airflow. Cultivation under protection also reduces dependency on chemical sprays by stabilizing growing conditions and enabling the use of biological control agents. At the same time, such enclosed systems require strict vigilance, as once pests establish inside, the closed environment favors rapid population growth. Sanitation practices, including removal of plant debris, weed control, and disinfection of tools, are critical for maintaining pest-free conditions. Use of sticky traps and pheromone-based monitoring inside greenhouses provides early warning signals and supports timely intervention.

D. Certification and phytosanitary compliance for exports

Export-oriented ornamental crop production is subject to strict phytosanitary regulations imposed by importing countries. Flowers destined for international markets must meet standards for pest freedom and residue levels, as outlined under global frameworks like the International Plant Protection Convention (IPPC). Crops must be produced, handled, and packaged in facilities that adhere to Good Agricultural Practices (GAP) and undergo inspection by authorized agencies. Detection of quarantine pests, such as certain species of thrips or scale insects, can result in shipment rejection and loss of export licenses. Integrated pest management that emphasizes non-chemical methods, monitoring tools, and pre-export treatment (e.g., cold storage or irradiation) is necessary to ensure compliance. Documentation such as pest-free certification, residue analysis reports, and traceability records form the backbone of export readiness in ornamental horticulture.

Research and Future Perspectives

A. Development of pest-tolerant varieties in spices and flowers

Advancement in crop breeding has led to the identification and development of pest-tolerant varieties, which form a sustainable foundation for integrated pest management (Fitt *et.al.,* 2012). In spice crops like chilli and coriander, significant progress has been made through conventional breeding and molecular tools in selecting lines resistant to thrips, aphids, and fruit borers. Some chilli genotypes exhibit tolerance to Scirtothrips dorsalis through traits such as thicker epidermal tissues and increased trichome density, which reduce pest feeding and oviposition. In ornamental crops, certain rose cultivars possess natural resistance to Macrosiphum rosae due to biochemical traits such as low nitrogen content in young leaves. Jasmine lines showing reduced infestation by *Leucinodes orbonalis* have been identified through field screening in multiple agroclimatic conditions. Development of such cultivars reduces the reliance on chemical pesticides and ensures safer, more resilient cropping systems. Biotechnology and marker-assisted selection continue to play a pivotal role in identifying quantitative trait loci (QTLs) linked to resistance, which can fast-track the breeding process.

B. Nanotechnology and precision pest monitoring tools

Emerging research in nanotechnology is offering innovative approaches for pest management and surveillance in high-value horticultural crops. Nano-formulations of insecticides such as nano-silver, nano-chlorpyrifos, and nano-neem exhibit enhanced bioefficacy at lower doses, controlled release properties, and reduced environmental footprint. These nano-agents provide longer residual activity and improve adhesion on waxy plant surfaces, a characteristic critical for crops like rose and turmeric. Precision monitoring tools are transforming pest detection and forecasting. Wireless sensor networks and automated image-based systems integrated with artificial intelligence are being tested to identify pest incidence in real-time. Remote sensing using drones and hyperspectral imaging enables spatial mapping of pest hotspots in large fields, enhancing the efficiency of targeted interventions. Mobile-based decision support systems provide farmers with real-time pest alerts and advisory services, improving the timeliness and accuracy of control measures. These tools align with sustainable intensification by reducing pesticide use and improving crop health outcomes.

C. Potential of entomopathogenic fungi and nematodes

Biological control using entomopathogenic fungi and nematodes is gaining importance due to its compatibility with eco-sensitive and residue-free crop production. Fungi such as Beauveria bassiana, Metarhizium anisopliae, and *Lecanicilliumlecanii* are effective against soft-bodied insects like aphids, whiteflies, thrips, and mites. These agents work by penetrating the insect cuticle, proliferating internally, and ultimately killing the pest. Their specificity to target pests and safety to non-target organisms make them suitable for use in spice and ornamental crops, particularly under organic and semi-organic production systems. Entomopathogenic nematodes such as *Steinernema carpocapsae* and *Heterorhabditis bacteriophora* are being explored to manage soil-dwelling pests including cutworms and root borers. These nematodes actively seek out insect hosts in the soil and release symbiotic bacteria that cause rapid mortality. Integration of these biological tools into mainstream pest management can reduce pesticide resistance, protect beneficial arthropods, and support biodiversity in agroecosystems.

D. Policy support for low-residue and eco-certified products

The growing demand for safe and sustainable agricultural produce is pushing policymakers and regulatory agencies to support low-residue production systems and promote eco-certification standards. Government initiatives are encouraging the adoption of integrated pest management through training programs, subsidies on biopesticides, and model demonstration plots. Certification schemes such as Good Agricultural Practices (GAP), Participatory Guarantee Systems (PGS), and organic certification require strict adherence to pest management protocols that limit synthetic chemical inputs. Export regulations from the European Union and Gulf countries mandate compliance with maximum residue limits (MRLs), prompting the need for residue monitoring laboratories and enforcement of traceability in production systems. Research institutions are also aligning with these goals by developing pest forecasting models, compiling pest risk analyses, and publishing threshold-based intervention schedules tailored for export-oriented crops. Strengthening public-private partnerships in biocontrol product development and creating farmer-level incentives for ecological compliance are crucial to advancing sustainable pest management in high-value horticulture.

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Chapter 7

Structural Entomology and Urban Pest Management

Sudhanshu Raikwar*[1] and Devina Seram[2]

[1]*Student, Department of Entomology, School of Agriculture, Lovely Professional University, Phagwara*

[2]*Assistant Professor, Department of Entomology, School of Agriculture, Lovely Professional University, Phagwara*

***Corresponding Author Email:** raikwarsudhanshu98@gmail.com

Structural entomology is the specialized field of entomology that focuses on insects and arthropods inhabiting human-built environments. It involves the study of biology, behavior, habitat preferences, and control of pests commonly found within residential, commercial, and industrial structures. This branch of entomology addresses insect species that damage buildings, contaminate food, transmit disease, or cause general nuisance. Structural entomologists work to understand how these pests interact with human environments and develop strategies for their prevention and management. The scope of this discipline includes wood-destroying insects, urban invaders, pantry pests, and medical pests that thrive under artificial shelter and benefit from stable food and moisture sources found indoors.

A. Importance of urban pest management in public health and hygiene

Urban pest management is critical for safeguarding public health and maintaining hygienic living conditions. Household pests such as cockroaches, flies, ants, and bedbugs are known to harbor and transmit a range of pathogens including Salmonella, Escherichia coli, and Staphylococcus aureus. Cockroaches, for example, are associated with allergens that exacerbate asthma in children, particularly in densely populated urban neighborhoods. Bedbugs may not transmit diseases but their bites cause irritation, psychological distress, and sleep disorders. Rodents, often overlapping in pest control efforts with insect management, contribute to the spread of leptospirosis and other zoonotic infections. Effective pest management thus becomes an essential component of urban sanitation programs, food safety initiatives, and disease prevention strategies.

B. Economic and structural impacts of household pests

Household pests impose significant economic burdens through both direct and indirect effects (Bebber *et.al.,* 2014). Termites, particularly *Coptotermesformosanus* and *Odontotermes obesus*, are capable of silently destroying the wooden framework of homes, furniture, and public infrastructure, often requiring costly repairs and reconstruction. Annual losses due to termite damage alone are estimated in billions globally. Stored food pests such as *Tribolium castaneum* (red flour beetle) and *Sitophilus oryzae* (rice weevil) reduce the quality and quantity of grains, cereals, and processed foods, leading to spoilage and consumer complaints. Indirect costs arise from the need for regular pest control services, loss of reputation in commercial establishments such as hotels and restaurants, and lowered property values. Pest-related health care expenses and absenteeism due to infestations also contribute to the overall economic toll.

C. Common pests found in homes, buildings, and urban settings

A wide range of pests adapt successfully to urban environments due to consistent food availability, artificial climates, and structural niches. Cockroaches such as *Blattella germanica* (German cockroach) and *Periplaneta americana* (American cockroach) are frequent invaders of kitchens, bathrooms, and drainage systems. Ants including *Monomorium pharaonis* (pharaoh ant) and *Tapinoma melanocephalum* (ghost ant) infiltrate pantries and electronics. Termites pose hidden threats to wood-based structures, while bedbugs (*Cimex lectularius*) infest mattresses, upholstery, and crevices in multi-occupancy dwellings. Other pests include silverfish (*Lepisma saccharina*), which damage paper and fabric; flies that breed in organic waste; and spiders or centipedes that enter homes as incidental invaders. Each of these pests requires a distinct management approach, but their presence reflects common lapses in sanitation, exclusion, or structural integrity. Their control demands an understanding of pest biology, building design, and environmentally responsible treatment methods.

Classification and Identification of Urban Pests

A. Insect pests associated with human dwellings

Urban pests are organisms that thrive in close proximity to humans, often exploiting man-made environments for shelter, food, and breeding. These pests include a wide array of insect species that adapt to the conditions found in residential buildings, commercial spaces, and public infrastructure. Common insect pests include cockroaches, ants, termites, bedbugs, flies, mosquitoes, silverfish, and stored product insects such as beetles and moths. These pests often gain entry through cracks, vents, drainage systems, and even packaging materials. Once established, they can survive in kitchens, bathrooms, basements, attics, and wall voids, using warmth, humidity, and readily available food to support their populations.

B. Morphological and behavioral traits of urban pests

Urban insect pests exhibit several distinct traits that make them successful invaders of human habitats. Morphologically, many are small-bodied, flattened, or flexible, allowing them to hide in tight crevices and remain undetected for extended periods.

Behavioral adaptations such as nocturnal activity, high reproductive potential, social colony structure, and aggregation pheromones enhance survival and reproduction. For example, the German cockroach (Blattella germanica) is highly prolific, with a female producing up to 400 offspring in her lifetime. Ants operate in colonies and display foraging trails, while bedbugs are cryptic and emerge primarily at night to feed. These pests often develop resistance to commonly used insecticides and show behavioral avoidance of treated surfaces, complicating management efforts. Their ability to exploit microhabitats and alternate food sources makes them persistent and difficult to eradicate without comprehensive control strategies.

C. Categories based on habitat and feeding behavior

Urban pests are best understood when classified according to their ecological niches and feeding patterns, which help in formulating appropriate control approaches.

1. Structural wood-destroying pests

These pests include termites such as *Coptotermes gestroi* and *Odontotermes obesus*, and wood borers like Lyctus brunneus. They damage wooden furniture, doors, beams, and flooring by tunneling and feeding on cellulose. Subterranean termites build mud tubes for movement and can cause extensive damage before detection. Their ability to remain hidden while infesting structural components makes them economically significant pests in urban environments.

2. Food-infesting pests

This group comprises beetles, weevils, and moths such as *Tribolium castaneum* (red flour beetle), *Sitophilus oryzae* (rice weevil), and Plodia interpunctella (Indian meal moth). These insects infest stored cereals, flours, nuts, spices, and packaged goods, contaminating food with feces, webbing, and exuviae. They thrive in storage cabinets, pantries, and warehouses, reducing food quality and causing losses in both domestic and commercial settings.

3. Blood-sucking pests

Species such as Cimex lectularius (bedbug), Pediculus humanus capitis (head louse), Pulexirritans (human flea), and mosquitoes including Aedes aegypti belong to this category. These pests feed on human blood and are associated with skin irritation, allergic reactions, and disease transmission. Bedbugs hide in mattress seams and crevices during the day and emerge at night to feed, while mosquitoes breed in stagnant water and are vectors of diseases such as dengue and chikungunya.

4. Nuisance pests

These pests may not always pose health threats or cause direct damage but are problematic due to their abundance, behavior, or unpleasant appearance (Ratnadass *et.al.,* 2012). Common nuisance pests include ants, houseflies (Musca domestica), crickets, and cockroaches. Though cockroaches can spread pathogens, their mere presence often causes anxiety and discomfort among residents. Nuisance pests affect quality of life and can tarnish reputations of hospitality businesses when visible to guests.

Cockroaches

A. Common species: *Periplaneta americana, Blattella germanica, Blattaorientalis*

Cockroaches are among the most persistent and objectionable pests found in human habitations. Several species dominate in urban environments, with *Periplaneta americana* (American cockroach), *Blattella germanica* (German cockroach), and *Blattaorientalis* (Oriental cockroach) being the most common. The American cockroach is the largest among these, typically reaching up to 50 mm in length, reddish-brown in color, and often infesting damp, dark areas such as basements, sewer lines, and utility tunnels. The German cockroach is smaller, light brown to tan, and characterized by two dark parallel streaks on the pronotum. It thrives in warm, humid environments, especially in kitchens and bathrooms. The Oriental cockroach is dark brown to black, less mobile than the others, and is usually associated with cool, damp environments such as drainage channels and cellar areas.

B. Habits, habitats, and reproductive potential

Cockroaches are nocturnal, thigmotactic insects that prefer narrow spaces, cracks, and crevices where they feel secure. They are scavengers, feeding on a wide variety of organic matter including food scraps, grease, glue, soap, and even hair. Their reproductive capacity is extremely high. A single female Blattella germanica can produce up to eight oothecae (egg cases) in her lifetime, each containing 30–40 eggs. Under optimal conditions, the population can grow exponentially. Nymphs develop rapidly in warm temperatures and are difficult to control due to their elusive hiding spots and resistance to many insecticides. They move rapidly when disturbed and often go unnoticed until infestations become severe.

C. Health implications and contamination pathways

Cockroaches are recognized as vectors of numerous pathogens that affect human health. They mechanically transmit bacteria, viruses, protozoa, and helminths as they move across contaminated surfaces and food preparation areas. Pathogens such as Salmonella, Shigella, Escherichia coli, and Staphylococcus aureus have been isolated from cockroach bodies and feces. Their droppings, shed skins, and secretions also act as allergens, contributing to asthma and other respiratory problems, particularly in children and sensitive individuals. Cockroach infestations degrade hygiene in food service establishments, pose risks in hospitals and residential areas, and can lead to food contamination, illness outbreaks, and regulatory violations.

D. Management strategies

Effective control of cockroach populations requires a multi-pronged approach focused on both elimination and prevention.

1. Sanitation and exclusion

Maintaining strict hygiene by eliminating food residues, grease build-up, and moisture is the cornerstone of cockroach management. Sealing entry points, repairing leaks, and covering drains and vents prevent access and harborage. Regular cleaning of kitchen appliances, garbage containers, and storage spaces is essential to reduce attractants.

2. Baits, gels, and residual sprays

Gel baits containing active ingredients such as fipronil, hydramethylnon, or imidacloprid are widely used due to their targeted action and minimal risk of exposure. Cockroaches are attracted to the bait, ingest it, and transfer toxic residues to nest mates through contact and feces, resulting in secondary kill. Residual sprays applied to cracks, baseboards, and voids provide long-lasting control. Rotating active ingredients helps delay resistance development.

3. Insect growth regulators (IGRs)

IGRs such as hydroprene and pyriproxyfen disrupt normal development in cockroach nymphs, preventing them from reaching reproductive maturity. These are used in conjunction with adulticides for comprehensive control. IGRs have low toxicity to humans and pets, making them suitable for indoor use.

4. Monitoring and IPM in domestic and commercial kitchens

Sticky traps placed along walls, under sinks, and near appliances help monitor cockroach activity and identify infestation zones. Integrated Pest Management (IPM) programs emphasize preventive practices, regular inspections, targeted treatments, and continuous monitoring. In food establishments, pest control records and compliance with public health standards are crucial. Educating building occupants on sanitation practices and early reporting also strengthens long-term management.

Ants

A. Major species: *Monomorium pharaonis* (pharaoh ant), *Solenopsis invicta* (fire ant), *Tapinoma melanocephalum* (ghost ant)

Ants are one of the most commonly encountered pests in urban environments. Their small size, diverse feeding habits, and highly organized colonies allow them to invade a wide range of structures. Among the most significant household ant species are *Monomorium pharaonis* (pharaoh ant), *Solenopsis invicta* (fire ant), and *Tapinoma melanocephalum* (ghost ant). The pharaoh ant is a tiny, yellowish insect that nests in wall voids, behind baseboards, and within electrical switch boxes. It is particularly problematic in hospitals, food establishments, and apartment buildings. The fire ant is more aggressive, known for its painful sting, and poses risks to humans and animals. It forms large mounds outdoors but often invades structures when disturbed. The ghost ant, identified by its pale legs and translucent abdomen, prefers high-humidity environments and is frequently found in kitchens and bathrooms, foraging for sugary materials.

B. Social behavior and nesting habits

Ants are eusocial insects organized into colonies comprising queens, workers, and males (Ross *et.al.,* 1995). Their success as urban pests is largely attributed to their complex social structure, which allows them to establish satellite nests and adapt quickly to changing environments. Many ant species exhibit polygyny, where colonies contain multiple queens, leading to rapid population growth. Nesting sites vary by species; pharaoh ants create their nests in warm, concealed indoor areas, while fire ants prefer soil and often build mounds in lawns, parks, or near building foundations. Ghost ants establish nests both indoors and outdoors, often relocating their colonies in response to disturbance or food scarcity. Trail pheromones guide foraging workers to food sources, resulting in long lines of ants appearing suddenly when food is detected.

C. Food sources and indoor nuisance

Ants are omnivorous and opportunistic feeders, consuming a wide range of food including sweets, proteins, grease, and even plant materials. Indoors, they are commonly attracted to sugar spills, pet food, and improperly stored items. Once a food source is located, foraging ants leave chemical trails that recruit others to the site, rapidly increasing their numbers. This behavior causes annoyance and disrupts sanitation, particularly in kitchens, restaurants, and food storage areas. Some species, like the pharaoh ant, are known to invade sterile environments such as hospitals, where they pose serious threats by accessing intravenous lines, wounds, and surgical instruments. Fire ants, due to their sting, can become dangerous in residential yards, posing a hazard to children and pets. The presence of ants in electronic equipment and power boxes is also documented, often leading to short circuits and mechanical failure.

D. Management approaches

Effective ant control requires understanding their nesting behavior and colony dynamics. Traditional contact insecticides may provide temporary relief but often fail to reach the queen or hidden satellite nests, leading to reinfestation. Comprehensive and sustained strategies are therefore essential.

1. Habitat modification

Reducing access to food, water, and shelter is a critical first step. Sealing entry points around doors, windows, and plumbing fixtures prevents indoor intrusion. Eliminating crumbs, storing food in airtight containers, and addressing leaks or excess moisture reduces attractants. Outdoor sanitation, such as managing garbage and removing organic debris, limits nesting opportunities near structures.

2. Baiting systems

Ant baits are formulated with slow-acting toxicants combined with attractive food sources. Worker ants carry the bait back to the nest and share it through trophallaxis, allowing the toxin to spread to the entire colony, including the queen. Baits using active ingredients like hydramethylnon, indoxacarb, or boric acid have proven effective for species such as pharaoh ants and ghost ants. The placement of baits along foraging trails, near nests, and in areas of activity is crucial for success. Patience is required, as it may take several days to weeks to achieve colony collapse.

3. Barrier sprays and perimeter treatment

Residual insecticides applied around building foundations, entry points, and along walls can prevent ants from entering structures. These barriers disrupt foraging trails and deter migration. Synthetic pyrethroids are commonly used for this purpose, though care must be taken to avoid contamination of indoor environments. For fire ants, direct mound treatments with drench solutions or granular insecticides can be effective in reducing outdoor populations.

4. Control challenges due to colony structure

Managing ants is complicated by their ability to bud new colonies and relocate nests when threatened. Polygynous colonies, in particular, are resilient to partial elimination and may split into multiple units under stress. Misapplication of repellents or contact insecticides can trigger this budding behavior, worsening infestations. Species identification is essential, as different ants exhibit unique nesting patterns, foraging behaviors, and bait preferences. Continuous monitoring and adjustments to the management plan are necessary to ensure complete elimination.

Termites

A. Subterranean and drywood termite species

Termites are among the most destructive structural pests worldwide, with their ability to silently consume cellulose-based materials leading to extensive damage in buildings, furniture, and wooden installations. The two main categories of termites that infest human structures are subterranean and drywood termites. Subterranean termites, such as *Coptotermes gestroi*, *Odontotermes obesus*, and Reticulitermes flavipes, live in soil and require moisture to survive. They build mud tubes to travel between their colony and food sources. Drywood termites like Cryptotermes brevis live entirely within wood, including dry timber, without requiring contact with the soil. These species are often found in doors, window frames, furniture, and flooring. Unlike subterranean species, drywood termites do not construct mud tubes, making them harder to detect in the early stages of infestation.

B. Damage to wooden structures and economic losses

Termites feed primarily on cellulose, which is found in wood and wood-based products. Their activity often goes unnoticed until significant damage has occurred, as they eat wood from the inside out. Subterranean termites are capable of compromising the structural integrity of beams, floors, walls, and support columns, resulting in costly repairs. Drywood termites hollow out wood pieces, leaving behind powdery frass and weakened internal galleries. The global economic impact of termite damage is substantial, with billions of dollars spent annually on repairs and control. In many urban areas, termites are considered the most economically significant household pest due to the scale and severity of damage they cause in both residential and commercial structures.

C. Life cycle and colony behavior

Termite colonies consist of a complex caste system that includes reproductives (king and queen), workers, soldiers, and, in some species, supplementary reproductives. The queen can live for over a decade and lay thousands of eggs, maintaining a robust and long-lived colony. Workers are responsible for foraging, feeding the colony, and maintaining the nest, while soldiers defend against intruders. Subterranean termites establish their colonies underground and build tunnels to forage above ground, sometimes reaching up to 45 meters in search of food. Drywood termites, form smaller colonies directly within the wood they consume. Swarmers, or alates, are winged reproductives that leave the colony to mate and establish new nests, often a sign of an active infestation when found indoors.

D. Detection methods

Detecting termites at an early stage is crucial for preventing structural damage and implementing timely control measures (Li *et.al.,* 2025).

1. Mud tubes and swarmers

Mud tubes constructed by subterranean termites serve as protective highways from the soil to wood structures. These are often visible on walls, foundations, or basement ceilings. Their presence is a reliable sign of infestation. Swarmers, which emerge during specific seasons, particularly in warm, humid conditions, may be spotted near windows or light sources. Finding discarded wings indoors also signals the presence of a colony.

2. Termite monitoring stations

These are devices placed around the perimeter of buildings to detect termite activity before structural damage occurs. They contain untreated wood or cellulose bait that attracts foraging termites. Once activity is confirmed, the station can be replaced with toxic bait to eliminate the colony. Monitoring systems play a vital role in Integrated Pest Management (IPM) for termites, especially in sensitive or high-risk areas such as heritage buildings and wooden-frame houses.

E. Termite control methods

A combination of preventive and remedial approaches is necessary to achieve long-term termite control.

1. Soil treatment and wood preservatives

Pre-construction soil treatment with termiticides like chlorpyrifos or fipronil creates a chemical barrier that prevents termites from entering buildings. Post-construction treatment involves drilling holes around infested areas and injecting termiticide into the soil. Treating wood with preservatives such as borates increases its resistance to termite attack and is especially useful for furniture and structural timber.

2. Bait systems and chemical barriers

Baiting systems use slow-acting toxicants incorporated into cellulose-based matrices. Termites consume the bait and carry it back to the colony, resulting in gradual death of the entire population. Products containing noviflumuron or hexaflumuron are commonly used. Chemical barriers, established through perimeter trenching and injection, prevent entry and are effective against subterranean species when applied correctly and maintained periodically.

3. Structural modifications for long-term control

Such as physical barriers, proper ventilation, and use of non-cellulose materials in foundation areas can help prevent infestations. Ensuring that wood does not come into direct contact with soil, repairing leaks, and maintaining dry conditions discourage termite activity. Architectural planning that includes termite shields and concrete slabs with sealed expansion joints offers long-term protection.

Bedbugs

A. Biology of Cimex lectularius and resurgence factors

Bedbugs, scientifically known as Cimex lectularius, are small, wingless ectoparasites that feed exclusively on the blood of warm-blooded animals, primarily humans (Doggett *et.al.,* 2012). Adult bedbugs are about 4–7 mm long, reddish-brown in color, and flattened dorsoventrally, which enables them to hide in narrow crevices. A single female can lay 200–500 eggs in her lifetime, with eggs hatching within 6–10 days under optimal conditions. Nymphs undergo five molts before reaching adulthood, requiring a blood meal at each stage. Their resurgence in recent decades has been attributed to increased global travel, movement of infested furniture, and resistance to commonly used insecticides such as pyrethroids. Infestations have become more prevalent in residential buildings, hotels, dormitories, and even public transport systems, often going unnoticed due to their elusive behavior.

B. Hiding behavior and nocturnal feeding

Bedbugs are cryptic insects that hide during the day in dark, secluded places such as mattress seams, box springs, bed frames, headboards, electrical outlets, curtain folds, and baseboards. Their flattened bodies enable them to fit into spaces as thin as a credit card. They are primarily nocturnal and become active during the pre-dawn hours when they are attracted to body heat and carbon dioxide. Feeding typically lasts 3–10 minutes, during which they inject saliva containing anticoagulants and anesthetics to facilitate blood flow without detection. After feeding, they retreat to their hiding places, making detection and control difficult. Infestations often spread as individuals move from one location to another, transporting bedbugs through luggage, clothing, or infested items.

C. Signs of infestation and health effects

Detecting bedbug infestations in the early stages is challenging but critical. Visible signs include rusty or reddish stains on sheets and mattresses caused by crushed bugs, dark spots of excrement, pale yellow shed skins, and live bugs in crevices. Bites are often the first indication, typically occurring in a line or cluster on exposed skin such as arms, legs, and neck. Although bedbugs are not known to transmit diseases, their bites can lead to itching, inflammation, and secondary skin infections due to scratching. Psychological impacts include anxiety, insomnia, and stress associated with the stigma and persistence of infestations. In sensitive individuals, bites may provoke allergic reactions, sometimes requiring medical attention.

D. Management strategies

Effective control of bedbug infestations requires a comprehensive and integrated approach, as these pests are highly resistant, resilient, and difficult to eliminate completely with single methods.

1. Mechanical removal and vacuuming

Vacuuming is a fundamental step in bedbug management. High-powered vacuums can remove live bugs, eggs, and debris from mattresses, box springs, bed frames, and baseboards. The vacuum bag must be sealed and disposed of properly to prevent re-infestation. Encasing mattresses and box springs in bedbug-proof covers also helps reduce harborage sites and exposes bugs to starvation.

2. Heat treatment and steam applications

Bedbugs and their eggs are susceptible to temperatures above 50°C. Professional heat treatments involve raising room temperatures to lethal levels for several hours, which penetrates furniture, walls, and other hiding places. Steam applications directed into cracks and crevices are particularly effective for spot treatments. These non-chemical methods are favored in sensitive areas such as hospitals and childcare centers.

3. Use of insecticides and dust formulations

Chemical control involves the application of residual insecticides to harborages and travel paths. Insecticide dusts containing silica gel, diatomaceous earth, or boric acid desiccate bedbugs upon contact. Pyrethroids and neonicotinoids are commonly used, though resistance has been widely documented. Insect growth regulators (IGRs) can inhibit development and reproduction. Repeated applications may be necessary, and thorough inspection is required to ensure coverage of all infested zones. Chemical treatments should be integrated with non-chemical methods to increase effectiveness and reduce the likelihood of resistance buildup.

4. Preventive measures in hotels and homes

Regular inspection and maintenance are vital in high-risk environments such as hotels and hostels. Staff should be trained to identify early signs of infestation. Linens, mattresses, and furnishings must be routinely checked. Minimizing clutter and sealing cracks in walls or furniture reduces potential harborage. Travelers should inspect hotel beds and avoid placing luggage on the floor or beds. Encasements for mattresses and proactive monitoring using intercept traps can help detect and contain early-stage infestations.

Long-term bedbug management emphasizes education, early detection, and multi-modal strategies combining physical, chemical, and environmental interventions. Successful eradication demands persistence and cooperation between occupants, pest professionals, and building managers.

Silverfish and Firebrats

A. Identification and habitats (book bindings, paper, fabrics)

Silverfish (*Lepisma saccharina*) and firebrats (*Thermobia domestica*) are primitive, wingless insects belonging to the order Zygentoma. Silverfish are characterized by their silvery-gray, metallic appearance and carrot-shaped body that tapers at the end, measuring around 12 mm in length. Firebrats are slightly darker, mottled gray or brown, and similar in size but better adapted to warm environments. Both species possess three long tail-like appendages and move in a quick, fish-like motion, which contributes to their common names. These insects prefer concealed, undisturbed indoor areas, often infesting bookshelves, storage boxes, wall voids, attics, basements, and around baseboards. They are commonly found among book bindings, paper, starched clothing, wallpaper, and fabrics that contain polysaccharides or glue-based adhesives.

B. Feeding habits and damage potential

Silverfish and firebrats are nocturnal scavengers that feed primarily on starchy substances, sugars, and proteins. Their diet includes glue, paper, cardboard, cotton, silk, linen, dead insects, and even dandruff. They are particularly attracted to materials with a high content of dextrin or adhesives, such as book bindings, wallpaper paste, and photographic paper. The damage they cause is not due to biting or chewing but rather from scraping and etching soft surfaces with their mandibles. As a result, their presence can lead to irregular holes, yellow stains, and surface erosion in books, documents, paintings, and textiles. Long-standing infestations in libraries, archives, and museums can compromise valuable and irreplaceable materials, making early detection critical.

C. Environmental conditions supporting infestation

These insects thrive in dark, moist environments with moderate to high humidity levels, typically above 70%. Silverfish prefer cooler areas, generally between 22°C to 27°C, while firebrats favor warmer environments exceeding 32°C, such as boiler rooms, heating ducts, and hot water closets. Poor ventilation, water leaks, and the accumulation of organic debris can significantly support the establishment and growth of populations. Infestations often remain hidden for extended periods due to their secretive nature, with activity mostly occurring at night. Because they are long-lived insects surviving up to 3 years and enduring long periods without food control becomes challenging once colonies are established.

D. Control measures

Effective control of silverfish and firebrats depends on modifying the environment, eliminating food sources, and using targeted chemical and physical treatments.

1. Moisture reduction and ventilation

Improving ventilation and reducing moisture are essential preventive steps. The use of dehumidifiers in damp basements, fixing plumbing leaks, and increasing airflow in enclosed spaces decrease relative humidity and make conditions less favorable for development. Regular inspections of hidden and less-frequented areas such as storage rooms and behind furniture help detect early signs of infestation.

2. Insecticidal dusts and traps

Application of insecticidal dusts containing boric acid, diatomaceous earth, or silica gel into cracks, voids, and wall junctions disrupts the protective wax layer on the insect's exoskeleton, leading to desiccation and death. Sticky traps baited with starchy substances can be deployed near bookshelves, electrical outlets, and under appliances to monitor and reduce populations. These traps are especially useful in non-chemical environments such as museums and libraries.

3. Sanitation and exclusion techniques

Maintaining cleanliness is critical for removing potential food sources and preventing harborage (Gil *et.al.,* 2024). Vacuuming infested areas, decluttering storage spaces, and sealing crevices and wall gaps deny entry and shelter. Storing books and archival materials in sealed containers, using acid-free paper, and elevating items off the floor minimize exposure. Sealing cracks with caulk or weather stripping also prevents reinfestation. Integrated approaches that combine physical, environmental, and chemical strategies are most effective in ensuring long-term control of silverfish and firebrats, especially in institutions where paper-based materials must be preserved without contamination. Consistent monitoring and environmental control are vital to limit damage and safeguard historical, academic, and domestic assets.

Integrated Urban Pest Management (IUPM)

A. Principles and components of IUPM

Integrated Urban Pest Management (IUPM) is a comprehensive approach designed to manage pest populations in urban environments with minimal risk to humans, property, and the environment. It emphasizes a combination of methods that are environmentally sound, economically viable, and socially acceptable. IUPM begins with the identification of the pest species, understanding its biology, ecology, and behavior, followed by assessment of infestation levels and environmental conditions contributing to its presence. The core components of IUPM include prevention, monitoring, correct pest identification, decision-making based on action thresholds, and the integration of multiple control tactics cultural, physical, biological, and chemical used in a coordinated manner to achieve sustainable pest suppression.

B. Role of environmental management and exclusion

Environmental management forms the backbone of IUPM, focusing on habitat alteration to eliminate or reduce the factors that allow pests to thrive. Proper waste disposal, repair of leaking water pipes, decluttering of storage areas, and improvement in ventilation significantly reduce the availability of food, water, and shelter. Exclusion techniques aim to physically block pest entry through structural modifications. This includes sealing cracks in walls and floors, installing door sweeps, using fine mesh screens on windows, and caulking gaps around utility lines. These actions limit access to indoor spaces and reduce the risk of infestation by pests such as cockroaches, ants, and rodents. Urban planning that includes pest-resistant architecture, drainage systems, and green spaces managed with care further enhances long-term prevention.

C. Non-chemical control methods

Physical and mechanical strategies are prioritized in IUPM to reduce reliance on synthetic chemicals. These methods include vacuuming insect harborages, using temperature-based treatments like freezing or heat, and deploying traps such as glue boards, pheromone traps, and mechanical exclusion devices. Biological control also plays an important role, particularly in the management of mosquitoes and flies, through the use of natural enemies like larvivorous fish, parasitic wasps, or entomopathogenic fungi. Insect growth regulators (IGRs), which interfere with the development of juvenile insects, are considered safer alternatives and effective against pests such as fleas, bedbugs, and cockroaches. These non-chemical methods are particularly suitable for sensitive environments such as hospitals, schools, food processing areas, and households with vulnerable individuals.

D. Monitoring and threshold-based decision-making

Surveillance is critical for making informed decisions in IUPM. Monitoring involves routine inspection and the use of tools like light traps, bait stations, and sticky traps to detect pest presence and track population trends. Thresholds are predetermined pest density levels at which control measures must be initiated to prevent unacceptable damage or nuisance. These thresholds vary by pest species and setting. The presence of a single bedbug in a hotel room may warrant immediate action, while several ants in a commercial kitchen may prompt sanitation reviews and localized treatment. This threshold-based approach minimizes unnecessary pesticide applications, reduces the risk of resistance, and ensures that interventions are timely and effective.

E. Role of pest control professionals and public awareness

The success of IUPM depends on the skill and knowledge of pest management professionals. Trained personnel conduct detailed inspections, apply interventions based on scientific principles, and educate clients on long-term prevention. Professional services ensure compliance with safety regulations and integrate eco-friendly products and practices tailored to specific site conditions. At the same time, public education plays a crucial role in achieving sustainable outcomes. Raising awareness among residents, facility managers, and urban planners about sanitation, structural maintenance, and behavioral practices helps create a culture of prevention. Community participation enhances the effectiveness of area-wide pest control initiatives, especially in densely populated zones where isolated action yields limited results. IUPM reflects a shift from reactive pest elimination to proactive management rooted in ecological understanding and risk minimization. As urban populations grow and environmental concerns rise, IUPM offers a scalable and responsible framework for protecting health, property, and quality of life in urban settings.

Health and Safetyin Urban Pest Control

A. Allergen and disease transmission by urban pests

Urban pests present significant health hazards through both direct and indirect pathways. Cockroaches, are well-documented carriers of allergens that trigger asthma and allergic rhinitis, especially in children and individuals with respiratory sensitivities. Their excreta, shed skins, and saliva contain potent allergenic proteins. Rodents such as Rattus norvegicus and Mus musculus are known vectors of numerous diseases including leptospirosis, salmonellosis, and hantavirus infections. Bedbugs, though not proven to transmit pathogens, can cause intense itching, secondary bacterial infections from scratching, and considerable psychological stress. Flies such as Musca domestica mechanically transmit over 100 pathogens, including E. coli, Salmonella, and Shigella, by landing on human food after contacting filth. Mosquitoes such as Aedes aegypti contribute to urban outbreaks of arboviral diseases like dengue, chikungunya, and Zika. Thus, controlling urban pest populations is not merely an issue of comfort but a critical aspect of public health.

B. Risks associated with misuse of chemicals indoors

The indoor use of insecticides without proper knowledge or precaution can lead to harmful consequences. Aerosols, foggers, and sprays often contain volatile organic compounds (VOCs) and organophosphates that may cause respiratory irritation, skin rashes, dizziness, and long-term health risks with prolonged exposure. Children, elderly individuals, and pets are particularly vulnerable due to their lower body mass and closer proximity to treated surfaces. Improper application—such as spraying on food-contact surfaces, excessive dosing, or failure to ventilate rooms—

can result in chemical residues that persist in indoor environments. Moreover, misuse of rodenticides and insecticides may lead to secondary poisoning of non-target organisms, including pets and beneficial insects. There is also the concern of pests developing resistance due to repeated use of the same chemical group, which further complicates control efforts and requires stronger, often more toxic, compounds.

C. Safe handling and application of household insecticides

The responsible use of insecticides begins with reading and adhering strictly to label instructions. Only products approved for indoor use should be selected, and application should target specific pest harborages rather than indiscriminate spraying. Gloves, masks, and protective clothing are essential during application, particularly with dusts, concentrates, or fumigants. Rooms must be ventilated adequately after treatment, and occupants should be kept away until surfaces are dry and fumes have dispersed. Baits and gel formulations are preferred over sprays for pests like ants and cockroaches due to their targeted delivery and minimal exposure risk. Pesticides should be stored securely, out of reach of children and animals, and never transferred to food or drink containers. Disposal of empty containers must follow guidelines to prevent contamination of soil and water resources.

D. Regulatory guidelines for urban pest control

Urban pest control is governed by national and local regulatory frameworks that ensure safety and efficacy in pest management practices (Chandler *et.al.,* 2011). Licensing of pest control operators, certification of applicators, and registration of pest control products are overseen by competent authorities such as the Central Insecticides Board and Registration Committee (CIBRC) under the Insecticides Act, 1968. Only registered formulations can be legally marketed and applied. Guidelines specify permissible active ingredients, maximum residue limits (MRLs), pre-harvest intervals (for urban agriculture), and safe re-entry periods for treated premises. Professional pest control operators must maintain records of pesticide use, observe safety intervals, and comply with health and fire safety norms. Urban health departments also play a role in surveillance and outbreak management related to vector-borne diseases. Adherence to these regulations protects both applicators and the public while promoting sustainable and responsible pest control practices. Prioritizing health and safety in urban pest management is essential for maintaining public well-being, reducing risks of chemical exposure, and achieving long-term control outcomes. An informed and regulated approach not only enhances the effectiveness of interventions but also supports a cleaner, safer urban living environment.

Emerging Trends in Urban Pest Management

A. Use of smart traps and digital surveillance

The integration of smart technologies into urban pest control is transforming traditional practices by enabling precise, data-driven interventions. Smart traps equipped with sensors, cameras, and wireless communication capabilities allow real-time detection and remote monitoring of pest activity. These systems can differentiate between pest species based on image recognition and movement patterns, transmitting data to centralized dashboards for analysis. This continuous surveillance reduces the need for manual inspection and provides accurate information on pest hotspots, seasonal trends, and movement patterns. Facilities such as food storage units, hospitals, and hotels benefit greatly from such automation, as it allows prompt action before infestations reach critical levels. Geospatial mapping of infestations through GPS-enabled devices also supports area-wide control strategies and urban planning for pest-resilient infrastructure.

B. Pheromone-based control and attract-and-kill strategies

Pheromones, which are chemical signals used by insects for communication, are being increasingly utilized in urban pest management for both monitoring and direct control. Mating disruption, a technique that releases synthetic sex pheromones into the environment, confuses males and reduces successful reproduction. This has proven effective for pests like stored product moths and cockroaches. Attract-and-kill strategies combine pheromone lures with toxicants in bait stations, selectively targeting pest populations while reducing the environmental load of broad-spectrum insecticides. Such techniques offer a species-specific, non-invasive, and residue-free method of pest suppression. Pheromone traps are also widely used to monitor infestation levels of pests such as ants, termites, and pantry beetles, allowing timely interventions based on actual population dynamics.

C. Bio-rational and eco-friendly urban pest solutions

Urban environments demand pest control methods that minimize health risks and environmental contamination. Bio-rational solutions such as entomopathogenic fungi (Beauveria bassiana), microbial insecticides (e.g., Bacillus thuringiensis), and botanical extracts like neem-based formulations are gaining popularity for their safety and target specificity. These agents exploit biological vulnerabilities in pest species without harming humans, pets, or beneficial organisms. Insect growth regulators (IGRs), which interfere with molting and reproductive processes, provide another effective control method with minimal toxicity. Adoption of eco-friendly practices is also supported by increasing consumer awareness and regulatory pressure to reduce chemical residues, particularly in urban farming and household settings. Organic certification requirements and environmental audits further encourage the use of sustainable pest management inputs.

D. Public-private collaboration in pest awareness campaigns

Education and outreach are essential components of successful urban pest control. Public-private partnerships (PPPs) are emerging as effective models to bridge gaps in knowledge and action. Collaborations between municipal authorities, pest control companies, academic institutions, and community organizations help design and deliver awareness programs that promote hygienic practices, structural maintenance, and safe pesticide use. Campaigns focusing on vector-borne disease prevention, household pest identification, and waste management have shown positive impacts on community participation and pest reduction. Such initiatives also play a critical role during outbreaks of pests like mosquitoes or bedbugs, enabling rapid information dissemination and coordinated response. By involving multiple stakeholders, these campaigns ensure that pest control is not only reactive but preventive and community-driven.

Case Studies and Urban IPM Models

A. Residential infestation scenarios and outcomes

Urban residential environments often experience infestations due to high population density, inadequate waste disposal, and structural vulnerabilities. A common scenario involves persistent cockroach infestations in multi-unit apartment complexes. In one documented example, a housing block with recurring infestations of Blattella germanica showed extensive harborages in kitchen cabinets, behind refrigerators, and near plumbing systems. Residents reported allergic symptoms, food contamination, and psychological distress. An Integrated Urban Pest Management (IUPM) intervention was implemented involving sanitation education, sealing of entry points, use of gel baits containing fipronil, and application of insect growth regulators. After eight weeks, monitoring data from baited sticky traps indicated a 90% reduction in the cockroach population. Regular follow-up and community participation were key to sustaining results, highlighting how a well-structured IPM program can significantly improve living conditions and reduce health risks.

B. Pest management in commercial food establishments

Food-handling facilities are particularly vulnerable to pests such as flies, cockroaches, and stored product insects. A case involving a bakery infested with *Tribolium castaneum* (red flour beetle) and Musca domestica (housefly) demonstrated the importance of combining environmental and chemical control measures. The infestation had resulted in customer complaints and regulatory warnings. An IPM strategy was adopted that began with thorough cleaning and removal of infested flour and raw materials. UV light traps were installed for fly control, and airtight containers were used to store dry goods. Crack and crevice treatments with residual insecticides were applied during non-operational hours.

Staff were trained in inspection and waste handling practices. Within three months, product contamination was eliminated, and the facility passed inspection with full compliance. This case demonstrates the role of tailored pest control plans and good hygiene practices in ensuring food safety and regulatory adherence.

C. School and hospital pest control case reviews

Sensitive environments such as schools and hospitals require pest control strategies that minimize chemical exposure while ensuring safety (Gouge *et.al.,* 2023). In one urban school plagued by recurring ant and rodent infestations, students had been exposed to visible trails of Monomorium pharaonis and signs of Rattus rattus activity in storerooms. The pest control intervention involved physical exclusion methods such as steel mesh covers for vents, rodent-proof storage bins, and removal of vegetation near foundations. Non-toxic bait stations were installed and monitored regularly. Classrooms were cleaned daily, and food consumption was restricted to designated areas. This IPM approach led to full control of the pest problem within eight weeks without the use of broad-spectrum pesticides. In a tertiary hospital facility, bedbug complaints in the patient waiting area triggered a comprehensive response. After confirming the presence of Cimex lectularius, pest professionals employed steam treatment and HEPA vacuuming on upholstered furniture. Affected areas were sealed off during treatment hours, and information was provided to patients and staff to prevent reintroduction. The infestation was eliminated with no chemical usage, demonstrating the effectiveness of mechanical methods in sensitive settings.

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Chapter 8

Post-Harvest Losses and Factors Affecting Stored Grain Quality

Viresh Sadashiv Jeur[1], Shridhar Nivas Banne[2] and Kalyani Ashok Jadhav[3]

[1]*Assistant Professor, Department of Entomology, Sharad College of Agriculture, Jainapur (Kolhapur, M.S.)*

[2]*Assistant Professor, Department of Plant Pathology, Sharad College of Agriculture, Jainapur (Kolhapur,M.S.)*

[3]*Assistant Professor, Department of Post-Harvest Management, Sharad College of Agriculture, Jainapur (Kolhapur,M.S.)*

Post-harvest grain management refers to the systematic handling of agricultural produce after harvest to ensure its preservation, safety, and quality until it reaches the end consumer. This includes drying, cleaning, grading, packaging, storage, and transport. The primary objective is to prevent deterioration caused by biotic and abiotic factors such as insect pests, fungi, moisture, and temperature fluctuations. Grains, being biologically active even after harvest, are highly susceptible to spoilage if not managed properly. Effective post-harvest practices contribute to reducing food losses, safeguarding nutritional quality, and extending the shelf life of commodities.

A. Global and national post-harvest loss statistics

Globally, post-harvest losses in cereals alone are estimated to range between 10% and 30%, varying by region, storage conditions, and grain type (Nath *et.al.,* 2024). According to the Food and Agriculture Organization (FAO), annual global grain losses exceed 400 million tonnes, representing a significant waste of food, resources, and labor. Losses occur during different stagesharvesting, drying, handling, and storage. In tropical climates, high humidity and temperatures accelerate spoilage, especially during storage. Reports from various national agricultural agencies suggest that storage losses for cereals can reach 8–10%, while losses for pulses and oilseeds may be even higher due to their greater vulnerability to insect and fungal attack. These figures translate into millions of tonnes of grain wasted annually, impacting food availability and economic returns.

B. Relationship between grain quality, food security, and farmer income

Grain quality is a determinant of marketability, nutritional value, and consumer acceptance. It encompasses physical characteristics like grain size, color, and uniformity; biological safety such as absence of mold, insects, and mycotoxins; and viability for seeds in the case of stored planting material. Deterioration in any of these parameters reduces the commercial value and usability of the produce. Food security is directly linked to the quantity and quality of food retained post-harvest. Losses during storage reduce the net availability of food grains, leading to increased imports, price volatility, and nutritional insecurity. For farmers, post-harvest losses result in direct income reduction. When grains are downgraded due to poor quality, they fetch lower prices in the market. Farmers may also face rejection from procurement agencies or incur penalties for failing to meet food safety standards. Reducing post-harvest losses not only strengthens food supply chains but also enhances farmer livelihoods by increasing the quantity of marketable surplus and preserving quality for premium pricing.

Nature and Extent of Post-Harvest Losses

A. Quantitative vs. qualitative losses

Post-harvest losses are broadly classified into quantitative and qualitative losses. Quantitative losses refer to the measurable reduction in the weight or volume of grains during the stages of handling, transport, and storage. These losses occur due to spillage, consumption by pests, microbial spoilage, or physical degradation. Rodents can consume up to 10 grams of grain per day per individual, and their droppings contaminate much more. Insects such as *Sitophilus oryzae* and Rhyzoperthadominica feed on stored cereals, causing hollowing of grains and weight loss. On the other hand, qualitative losses denote the decline in grain quality in terms of nutritional value, palatability, seed viability, and safety. These are not always visible but may include fungal contamination leading to mycotoxin production, off-odors from rancid oils in oilseeds, discoloration, or reduction in protein and starch content. Even small levels of aflatoxin B1, produced by Aspergillus flavus, can render grain unsafe for human or animal consumption.

B. Estimated percentages of losses in major cereal and pulse crops

Various scientific assessments and surveys across tropical regions have documented significant losses post-harvest. Cereal crops like rice, wheat, and maize experience average storage losses between 5% and 12% under traditional storage systems. Pulses are more susceptible to bruchid beetles such as *Callosobruchus chinensis*, with post-harvest losses often reaching 10% to 15% within just a few months of storage if untreated. In maize, combined losses from rodents and insects can exceed 20% in poorly ventilated stores. Oilseeds such as groundnut and soybean are prone to lipid oxidation and mold contamination, resulting in losses that can exceed 10% in humid storage conditions. Moisture content above safe storage limits (usually 12–14% for most cereals) is a primary driver of fungal infestation and loss acceleration. These loss figures vary by region, season, and storage infrastructure, but consistently indicate a major gap in the post-harvest supply chain.

C. Economic implications for producers and consumers

Post-harvest losses directly affect the financial returns of farmers by reducing the quantity and quality of grains that can be sold or used for planting. Loss of even 10% of stored grain across a farming community can amount to hundreds of tonnes annually, translating into substantial income loss at local and national scales. The cost of replacing spoiled food, purchasing grain during lean periods, or importing to fill deficits adds financial strain on governments and consumers. Market prices may also rise when local supply is diminished due to hidden storage losses, affecting food affordability. In export-oriented systems, poor grain quality due to infestation or contamination leads to rejection at border checkpoints, resulting in economic penalties and loss of international trade credibility. On the consumer end, reduced access to affordable and safe grains can result in dietary deficiencies and health concerns. Investing in loss-reduction strategies such as improved storage, better handling, and pest management not only improves food security but also contributes significantly to national economic resilience.

Factors Affecting Stored Grain Quality

A. Physical factors

1. Moisture content of grains at storage

Moisture content of grains at storage plays a critical role in maintaining the viability and quality of stored grains. When moisture content exceeds the recommended safe limit of 12%–14% for most cereals and 8%–10% for pulses and oilseeds, it creates a favorable environment for microbial growth, mold proliferation, and insect development. Grains stored with high moisture are also susceptible to respiration-related heat buildup, leading to "hot spots" that accelerate spoilage. Improper drying prior to storage remains one of the leading causes of mold-related damage and mycotoxin contamination.

2. Grain temperature and surrounding air temperature

Grain temperature and surrounding air temperature determine the metabolic activity of both the grain and potential storage pests. High temperatures enhance insect reproductive rates and enzymatic degradation of seed tissues. For example, at temperatures around 30°C, *Sitophilus oryzae* can complete a life cycle in less than four weeks, dramatically increasing infestation intensity. Elevated grain temperatures also increase moisture migration within storage structures, leading to condensation on surfaces and subsequent mold growth in cooler zones.

3. Relative humidity in storage environments

Relative humidity in storage environments directly impacts grain equilibrium moisture content (Sawant *et.al.,* 2012). When ambient relative humidity exceeds 70%, grains tend to absorb moisture from the air, even if initially dried to safe limits. Sustained exposure to relative humidity above 65% favors fungal growth, while above 75%, conditions become ideal for Aspergillus flavus to produce aflatoxins. Fluctuations in humidity contribute to condensation cycles within bins and cause spoilage pockets that are often difficult to detect early.

B. Biological factors

1. Insect infestation (e.g., Sitophilus oryzae, Rhyzoperthadominica)

Insect infestation is one of the most damaging biological factors affecting stored grain quality. Pests such as *Sitophilus oryzae* (rice weevil) and Rhyzoperthadominica (lesser grain borer) bore into grains, reducing bulk weight, nutritional value, and germination potential. Their feeding activity generates heat and moisture, creating microenvironments conducive to secondary infestations and microbial activity.

2. Fungal contamination (e.g., Aspergillus, Penicillium)

Fungal contamination is another major concern in long-term storage. Fungi such as Aspergillus, Penicillium, and Fusarium species colonize grains and produce mycotoxins under warm and moist conditions. These toxins, particularly aflatoxins and ochratoxins, pose serious health hazards and are tightly regulated in international trade. Moldy grains also lose taste, color, and commercial acceptability.

3. Rodents and birds

Rodents and birds contribute significantly to both quantitative and qualitative losses. Rodents such as Rattus rattus and Mus musculus consume grains directly and contaminate much larger volumes with urine, droppings, and hair. Bird activity near storage structures leads to spoilage from pecking, fecal matter, and physical disruption of packaging or storage bins. Their presence also promotes the spread of mites and pathogens.

4. Mite and microbial activity

Mite and microbial activity intensify under warm and humid conditions. Storage mites such as Acarus siro thrive in flour and broken grains, contributing to allergen accumulation and spoilage. Microbial activity, including bacteria like Bacillus and Pseudomonas species, accelerates degradation of stored grain protein and lipids, creating off-flavors and leading to unacceptable changes in product texture.

C. Chemical factors

1. Residue accumulation (pesticides, fumigants)

Residue accumulation from repeated use of pesticides and fumigants can compromise grain safety. Improper or excessive chemical use leaves residues above permissible levels, which can result in food safety violations and rejection of export consignments. Chemical residues also pose risks to consumers, storage workers, and surrounding environments.

2. Oxidation of grain lipids

Oxidation of grain lipids occurs when grains—especially oilseeds such as groundnut, soybean, and mustard—are exposed to oxygen and elevated temperatures. Lipid peroxidation not only reduces the nutritional and market value of the grains but also produces rancid flavors and unpleasant odors, rendering the product unsuitable for human consumption.

3. Development of off-odors and discoloration

Development of off-odors and discoloration is a cumulative result of microbial metabolism, insect activity, and oxidation. Grains affected by fungal growth often develop a musty odor and may show visible black, green, or yellow discoloration depending on the mold species. Discolored or foul-smelling grains are automatically downgraded during procurement or quality testing and are often unfit for food or feed use. Understanding and managing these physical, biological, and chemical factors is crucial for preserving stored grain quality. Failure to address these aspects leads to significant losses in both volume and value, affecting producers, supply chains, and consumers alike. Scientific storage techniques, routine monitoring, and integrated pest and moisture management are essential for minimizing these risks and ensuring long-term food security.

Impact of Storage Duration and Conditions

A. Changes in germination capacity over time

The germination ability of stored grain seeds declines progressively as storage duration increases, especially under suboptimal environmental conditions. This reduction is primarily due to the natural aging of seeds, which accelerates when stored at high moisture content and elevated temperatures. Viable seeds require low moisture levels typically under 12% for cereals and 10% for pulses to maintain physiological activity without triggering respiration and deterioration. As grains respire, the accumulation of metabolic by-products such as carbon dioxide and heat can lead to oxidative stress and membrane degradation in seed cells. Studies show that after six months of storage under humid conditions, germination rates in untreated paddy seeds can drop by more than 25%. Pulses, being rich in protein and oil, are even more susceptible to viability loss, particularly chickpea and pigeon pea, which exhibit significant declines in germination within four to five months under poor storage.

B. Influence of ambient conditions on spoilage rates

Ambient temperature and relative humidity exert a direct influence on microbial and insect development, which are key drivers of grain spoilage. When the relative humidity exceeds 70% and temperatures remain above 25°C, mold growth is triggered even if the grain was initially dried to acceptable levels. The grain equilibrium moisture content adjusts dynamically based on surrounding conditions, leading to moisture gain and condensation inside containers or bins. This process creates microenvironments ideal for fungal colonization, particularly by Aspergillus and Penicillium species, which degrade carbohydrate and lipid reserves. At higher ambient temperatures, insect pests such as *Sitophilus oryzae* complete more life cycles within a season, thereby increasing infestation density. Research data show that under storage conditions of 30°C and 80% relative humidity, the storage life of maize can be reduced to under three months without protective treatments. These conditions also elevate the risk of aflatoxin production, especially in oil-rich grains, leading to loss of food safety and nutritional value.

C. Effect of packaging material and storage design on grain preservation

The choice of packaging material and the structural design of storage systems critically influence the extent of grain loss (Kumar *et.al.,* 2017). Permeable materials such as jute or cloth sacks allow air and moisture exchange, which, although suitable for short-term storage, promote pest invasion and mold development during prolonged storage. Hermetic storage options, including high-density polyethylene bags and metal silos, significantly reduce oxygen exchange and moisture ingress, thereby limiting insect respiration and fungal growth. The Purdue Improved Crop Storage (PICS) bags, designed with multiple layers of polyethylene, have been shown to reduce post-harvest grain loss by over 90% in traditional storage scenarios. Storage structures that incorporate ventilation, raised platforms, and rodent-proofing measures consistently report lower spoilage rates. Flat storage facilities with poor drainage or unsealed walls are prone to pest entry and moisture seepage, accelerating quality deterioration. Proper design also includes regular fumigation systems and moisture control techniques that help maintain grain quality for up to a year or more, especially when combined with pre-storage cleaning and drying. Therefore, both storage duration and the surrounding environment must be managed through science-based practices to ensure long-term grain preservation and food security.

Pre-Harvest Factors Influencing Storage Quality

A. Crop maturity and harvesting practices

The physiological maturity of a crop at the time of harvest plays a critical role in determining its subsequent storage quality. Grains harvested either prematurely or too late often exhibit compromised structural integrity, increased moisture content, and susceptibility to mechanical damage during handling. Immature grains typically contain higher levels of moisture and incompletely developed starch reserves, making them more prone to fungal colonization and rapid degradation during storage. Over-mature grains may shatter easily or develop field mold due to exposure to unpredictable weather conditions during the late stages of ripening. Timely harvesting at optimal moisture levels usually between 20%–25% for field harvesting and later dried to below 14% for cereals ensures a better balance of weight, durability, and physiological stability. Mechanized harvesting reduces losses through efficient grain collection but may contribute to kernel damage if calibration is improper. Manual harvesting, if delayed due to labor shortages or rain, results in increased vulnerability to pre-harvest sprouting and fungal colonization, which directly affects storability.

B. Threshing, cleaning, and drying efficiency

Post-harvest processing steps such as threshing, cleaning, and drying form the first line of defense against storage-related deterioration. Incomplete or aggressive threshing often results in broken grains, which are more susceptible to weevil infestation and fungal colonization. Clean grains are less prone to storage losses, as the removal of chaff, weed seeds, and broken particles eliminates primary refuges for insect pests and mold spores. Use of mechanical cleaners improves uniformity in grain size and aeration. Drying, particularly sun drying on clean surfaces, is crucial to reducing grain moisture to safe levels for storage. Studies have shown that even a 2% difference in moisture content (e.g., storing maize at 16% instead of 14%) can result in a threefold increase in fungal growth within three months. Poor drying techniques, such as drying directly on bare soil, lead to contamination with fungal spores, dirt, and other foreign matter. Delays in drying or incomplete drying cause moisture accumulation during storage, thereby creating a favorable microclimate for spoilage.

C. Varietal differences in storability

Genetic variation among crop varieties contributes significantly to the inherent storability of grains. Some cultivars possess natural resistance to storage pests due to harder seed coats, smaller size, lower oil content, or specific biochemical constituents such as phenolics and alkaloids that deter insects and fungi. Traditional rice varieties with high husk density and compact grain structure often show better resistance to *Sitophilus oryzae* infestation than modern high-yielding types with softer kernels. Similarly, pulses like pigeon pea and cowpea vary in their susceptibility to *Callosobruchus chinensis* based on seed hardness and seed coat color. Oilseeds with low linoleic acid content tend to have better shelf life due to reduced oxidation potential. Selection of varieties bred for storage tolerance can significantly reduce dependency on chemical treatments post-harvest. In many cases, farmers choosing high-yielding hybrids without considering their storability face unexpected grain losses during prolonged storage, especially under ambient conditions lacking temperature or humidity control. Thus, pre-harvest decisions regarding variety selection and harvest operations determine the long-term physical and economic viability of stored produce.

Post-Harvest Handling and Its Role in Quality Maintenance

A. Importance of proper drying techniques

Drying stands as the most critical step in post-harvest handling for ensuring safe storage and preserving grain quality. Moisture levels in freshly harvested crops typically range between 18% and 25%, which are unsuitable for storage due to the high risk of fungal growth, rapid insect multiplication, and grain respiration. Reducing grain moisture to below the safe storage threshold commonly 12% for cereals and 10% for pulses prevents biological degradation and chemical deterioration. Improper drying results in internal grain cracking, which compromises seed viability and facilitates easier penetration by pests. Use of solar drying on raised platforms, concrete floors, or tarpaulins allows for even moisture removal, while avoiding contamination from soil-borne fungi and dirt. Artificial drying using mechanical dryers offers precision and speed, particularly during monsoon periods, when sun drying is not feasible. Temperature control during mechanical drying is essential; excessive heat above 45°C can denature enzymes and reduce the germination potential of seed grains. Uniform and timely drying not only ensures better storage outcomes but also reduces the need for excessive chemical intervention.

B. Grading and sorting to remove immature or damaged grains

Grading and sorting contribute directly to the maintenance of grain quality by eliminating non-uniform, shriveled, broken, discolored, or pest-damaged grains from storage lots. These defective grains tend to deteriorate faster due to their compromised structure and serve as primary hotspots for insect infestations and microbial colonization. Sorting enhances bulk uniformity, improves aeration, and reduces the formation of moisture pockets. Machine-assisted grading systems separate grains based on size, weight, and optical properties, allowing higher precision than manual sorting. Removal of weed seeds, dust, and other foreign materials prevents cross-contamination and improves the marketability of produce. In seed processing facilities, sorting also eliminates genetically off-type or diseased grains that could compromise seed lot quality. Data from storage trials indicate that exclusion of as little as 5% of poor-quality kernels before storage can reduce the incidence of fungal growth by more than 60% over a six-month period.

C. Transportation and handling practices that minimize breakage

Mechanical damage to grains during loading, unloading, and transport significantly affects storage quality by increasing the surface area exposed to microbial attack and reducing grain durability (Sharma *et.al.,* 2023). Breakage leads to loss of structural integrity, accelerating spoilage and reducing economic value, particularly in export and seed markets. During bulk transport, vibrations and repeated impact in poorly designed containers or vehicles increase the percentage of broken grains. Using rubberized conveyors, padded containers, and low-drop loading mechanisms can minimize impact injury. Moisture gain during transit especially during long-distance haulage in humid regions further increases vulnerability to fungal contamination and clumping. Use of moisture-proof packaging materials such as high-density polyethylene bags or hermetic liners helps preserve grain condition during movement. Proper stacking and ventilation in transport containers prevent condensation and heat buildup, both of which contribute to grain spoilage. Careful handling across the entire supply chain from farm to storage facility ensures that the physical, nutritional, and commercial value of grains remains intact until final utilization or sale.

Traditional and Modern Storage Structures

A. Traditional storage systems (mud bins, bamboo structures, underground pits)

Traditional storage systems have been used for centuries to preserve grains under local climatic and socioeconomic conditions. These include mud bins, bamboo or wooden granaries, earthen pots, and underground pits. Mud bins, often constructed with a mixture of clay, cow dung, and straw, are used for storing cereals such as wheat and sorghum. They offer basic insulation against temperature fluctuations and are affordable, but they are vulnerable to moisture ingress, rodent damage, and insect infestations. Bamboo or wooden structures are typically elevated on stilts to reduce rodent entry and allow ventilation, but their porous nature makes them susceptible to attack by bruchids and fungal spores, especially under humid conditions. Underground pits are another common traditional method, especially for storing pulses and millet. While they offer protection from sunlight and theft, their lack of aeration often leads to rapid moisture buildup and fungal proliferation if not properly lined or sealed. These traditional systems generally lack airtightness and temperature control, limiting their long-term storage potential.

B. Improved structures (metal bins, Pusa bin, silos, hermetic bags)

Modern storage technologies have been developed to address the shortcomings of traditional systems and to meet the demands of longer storage durations and larger volumes. Metal bins made of galvanized iron sheets are widely adopted for storing cereals and pulses due to their resistance to rodents and insects. These bins are designed with tight-fitting lids and are often placed on raised platforms to reduce contact with soil moisture. The Pusa bin, developed by the Indian Agricultural Research Institute, is a modified underground storage structure with a cement base and polythene lining that improves moisture control and protects grains from pests. Vertical silos, used in both community and commercial storage, offer bulk storage capacity, mechanical aeration, and fumigation provisions, making them highly efficient for preserving grain quality. Hermetic storage bags, such as triple-layer Purdue Improved Crop Storage (PICS) bags, create an oxygen-deprived environment that halts insect development without the use of chemicals. These bags are especially effective in protecting pulses and maize from storage pests for several months. Data from field evaluations indicate that grain loss in hermetic bags is typically less than 1%, compared to up to 10% in jute or cloth sacks.

C. Design parameters that influence protection from pests and spoilage

The effectiveness of any storage structure is largely dependent on specific design parameters, including material type, seal integrity, ventilation, and protection from environmental exposure. Airtightness is critical in preventing insect respiration and fungal activity. Structures must be impermeable to water vapor and oxygen to minimize biological activity inside the storage unit. The elevation of the base, drainage around the structure, and use of rodent guards reduce pest access and dampness-related spoilage. Thermal insulation, achieved through materials such as reflective coatings or shaded roofing, helps maintain low internal temperatures, slowing down enzymatic and microbial degradation. Ventilation systems are essential in bulk storage silos to prevent hotspots caused by grain respiration, which can lead to localized mold outbreaks. Regular cleaning, repair of cracks, and pest-proof sealing are necessary maintenance practices to extend the usability of both traditional and modern structures. The combination of structural soundness, environmental isolation, and ease of fumigation or treatment defines the success of storage systems in maintaining grain integrity over time.

Role of Grain Moisture in Storage Losses

A. Safe moisture limits for storage of cereals, pulses, and oilseeds

Grain moisture content plays a pivotal role in determining the success or failure of long-term storage. Each category of grain has specific safe moisture thresholds, beyond which the risk of biological and chemical degradation increases sharply. For cereals such as wheat, rice, and maize, the recommended safe storage moisture content is around 12% or lower. Pulses, being more prone to bruchid infestation and fungal colonization, require moisture levels below 10%. Oilseeds like groundnut and mustard, which are highly susceptible to lipid oxidation and aflatoxin contamination, must be stored at moisture contents below 8%. Exceeding these limits accelerates metabolic activity, microbial growth, and insect development, leading to quality deterioration, discolouration, mustiness, and mycotoxin production. Empirical studies have demonstrated that wheat stored at 14% moisture content can experience over 30% quantitative and qualitative losses in six months under ambient tropical conditions, while maize at 16% moisture content supports full life cycles of storage pests such as Sitophilus zeamais and *Tribolium castaneum*.

B. Moisture migration and condensation problems

Moisture migration refers to the movement of water vapor within stored grain masses, driven by temperature gradients between the grain and the surrounding environment. During cooler nights and warmer days, temperature differences between the outer and inner grain layers lead to vapor condensation, especially near the top layers and walls of the storage unit. This localized increase in moisture creates "hotspots" that encourage fungal activity and clumping of grains. Condensation problems are common in metal silos or sealed structures where thermal insulation is poor and aeration is absent. These microenvironments foster the growth of storage molds like Aspergillus flavus, which produces harmful aflatoxins under high humidity conditions. Moisture accumulation also contributes to caking, spoilage, and reduction in germination rates. To mitigate such effects, proper insulation, use of ventilated roofing, and frequent grain stirring in bulk storages are essential practices. Monitoring grain temperature and relative humidity using sensors helps in predicting and preventing moisture-related damage.

C. Techniques for moisture control (solar drying, mechanical dryers, desiccants)

Effective moisture control begins at the field level and continues through post-harvest stages until storage (Magan *et.al.,* 2007). Solar drying is the most accessible and cost-effective method employed in rural and semi-urban regions. Grains are spread on raised platforms, plastic sheets, or concrete floors and stirred regularly for uniform drying. Although highly economical, solar drying is weather-dependent and may introduce contamination if conducted on bare soil or under high humidity. Mechanical dryers, such as batch-type or continuous-flow dryers, offer controlled drying with regulated air temperature and humidity. These systems are especially useful during monsoon periods and for large-scale operations. Overheating during mechanical drying must be avoided to prevent cracking and reduction in seed viability. Desiccants, including silica gel or calcium chloride-based compounds, are used in hermetic storage or seed preservation to maintain low moisture atmospheres. Hermetic containers prevent moisture ingress from the environment and inhibit insect respiration through oxygen depletion. Integration of drying technologies with proper moisture monitoring tools ensures that grains are stored within biologically safe parameters, minimizing losses and extending shelf life.

Temperature Management in Stored Grains

A. Optimum temperature range for long-term storage

Temperature plays a crucial role in determining the viability, quality, and shelf life of stored grains. The optimum temperature range for long-term storage lies between 15°C and 20°C, where both insect activity and fungal growth are significantly inhibited. Temperatures above 25°C are considered conducive for the rapid proliferation of common storage pests such as *Tribolium castaneum*, *Sitophilus oryzae*, and Rhyzoperthadominica. At temperatures exceeding 30°C, the rate of grain respiration increases, leading to higher moisture accumulation in the surrounding environment, which further escalates the risk of microbial spoilage. On the lower end, temperatures below 10°C can render insect eggs dormant or lead to mortality in immature stages, making such conditions ideal for preserving high-value seeds and export-quality produce. Prolonged storage of grains at elevated temperatures accelerates the degradation of nutritional compounds such as proteins and vitamins, while also increasing free fatty acid levels in oilseeds, which directly affects their market value. Thus, maintaining the temperature within the ideal physiological limits ensures the grain remains biologically inactive and structurally sound over extended storage periods.

B. Aeration methods to reduce temperature buildup

Aeration serves as a critical management tool to regulate the internal temperature of grain masses during storage. Forced aeration involves the use of blowers and duct systems to move ambient air through stored grains, which helps dissipate excess heat and reduce moisture pockets. This process is especially important during seasonal transitions when external weather changes induce temperature gradients inside storage units. Aeration fans are typically placed at the bottom of bins or silos, allowing cool air to flow upward through the grain bulk, gradually lowering the overall temperature. The success of aeration depends on factors such as air flow rate, humidity, and grain bulk density. Use of automated temperature monitoring systems coupled with aeration controls ensures efficient cooling without causing condensation. Natural ventilation, though less precise, can also be employed in small-scale storage using ventilated bins and raised platforms. Studies have shown that regular aeration can reduce average grain temperatures by 8–12°C during hot seasons and thereby decrease insect populations by over 70% within three months. Aeration also prevents the development of hotspots, which are localized zones of increased microbial and insect activity that lead to spoilage and mycotoxin production.

C. Role of temperature in insect and fungal development

Temperature directly influences the development rate, reproduction, and survival of insects and fungi within stored grain ecosystems. Most stored product insects have an optimal development range between 28°C and 35°C. For example, the life cycle of *Sitophilus oryzae* can be completed in just 25 days at 30°C, but the duration doubles if the temperature drops to 20°C. This indicates that maintaining temperatures below critical thresholds significantly slows pest population buildup. Similarly, storage fungi such as Aspergillus flavus and Penicillium species thrive at warm temperatures above 25°C, especially when relative humidity exceeds 70%. Temperature influences not only fungal growth but also the biosynthesis of harmful mycotoxins such as aflatoxins and ochratoxins, which pose serious health risks and lead to trade rejections in export markets. Cold storage, when economically feasible, has been demonstrated to halt all insect development and extend seed viability for over 12 months in pulses and oilseeds. Thus, the role of temperature is multifaceted, acting both as a catalyst for deterioration and a tool for preservation, depending on how it is managed throughout the storage cycle.

Fungal and Mycotoxin Contamination

A. Major fungal species affecting stored grains

Fungal contamination in stored grains is a significant post-harvest issue that compromises both food safety and economic value. The most common fungal genera associated with stored grains are Aspergillus, Penicillium, and Fusarium. Among these, Aspergillus flavus and Aspergillus parasiticus are the primary producers of aflatoxins, while Penicillium verrucosum is linked to ochratoxin production. These fungi are capable of colonizing grain kernels either pre-harvest under field conditions or post-harvest during storage. Fusarium species, particularly Fusarium verticillioides and Fusarium graminearum, are major contaminants in maize and wheat, producing fumonisins and deoxynivalenol, respectively. These fungi gain entry through damaged grains, high humidity environments, and poor aeration in storage structures. Contamination is typically most severe in cracked, immature, or insect-damaged kernels that provide easy access for fungal invasion.

B. Conditions promoting aflatoxin and ochratoxin production

Mycotoxin synthesis is not only a result of fungal growth but also heavily influenced by environmental conditions. Aflatoxin production by Aspergillus flavus is favored by high temperatures above 27°C and relative humidity above 70%. Grain moisture content above 14% serves as a catalyst for fungal metabolism, creating ideal conditions for mycotoxin biosynthesis. Ochratoxins, produced primarily by Penicillium verrucosum, tend to accumulate under cool, damp storage conditions with poor ventilation, particularly in temperate or high-altitude regions. Improper drying, delay in threshing, and use of unclean or previously infected storage units can also contribute to contamination. Research has shown that aflatoxin levels in maize stored at 16% moisture content for three months can exceed 20 parts per billion (ppb), which is beyond the permissible limit for human consumption. Lack of monitoring and delayed grain movement from field to storage increase the risk of toxin accumulation, particularly in monsoon or humid climates.

C. Health risks and trade limitations due to mycotoxin presence

Mycotoxins represent one of the most dangerous forms of biological contamination in the food chain (Galvano *et.al.,* 2005). Aflatoxins are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC) and are associated with liver cancer, immune suppression, and stunted growth in children. Ochratoxins are nephrotoxic and linked to kidney damage and potential carcinogenicity. Chronic exposure to even low levels of mycotoxins can result in long-term health disorders in humans and animals. From an economic perspective, contaminated grains face strict rejection in both domestic and international markets. Many countries have set maximum residue limits (MRLs) for aflatoxins at 4 ppb in food-grade commodities, and consignments exceeding these thresholds are often destroyed or returned. Such trade barriers severely affect the profitability of farmers and exporters. The presence of mycotoxins also limits the use of contaminated grain for livestock feed, as they reduce feed intake, impair reproduction, and lower immunity in animals. As a result, effective management of fungal contamination and routine testing for mycotoxins are vital for ensuring food safety, maintaining nutritional quality, and meeting global trade standards.

Rodents and Birds as Storage Pests

A. Damage mechanisms by rats and birds

Rodents and birds represent major vertebrate pests of stored grain systems, causing extensive physical losses and contamination. Rats, particularly species such as Rattus rattus (roof rat) and Bandicota bengalensis (lesser bandicoot rat), damage stored commodities through gnawing, nesting, and hoarding behavior. Their sharp incisors enable them to chew through wood, plastic, jute, and even metal mesh linings used in storage bins. One rat is capable of consuming up to 15–20 grams of grain daily, and the loss due to contamination through urine, feces, and hair can exceed the quantity of grain consumed. Birds such as pigeons, sparrows, and mynas often perch around storage godowns, spilling and spoiling grain while feeding. Their droppings introduce microbial contaminants, including Salmonella and E. coli, which pose direct risks to food safety. The pecking activity by birds on grain heaps also results in broken kernels, which deteriorate faster under humid conditions.

B. Signs of infestation and economic impact

Infestation by rodents and birds is often indicated by the presence of droppings, gnawed materials, tracks, nests, or direct visual sightings. In enclosed storage systems, scratching noises, holes in bags or bins, and displaced grains are common indicators of rodent activity. Birds leave behind feathers and faecal matter, typically concentrated near roof edges or open storage areas. The economic impact of these pests extends beyond direct consumption. Contaminated grain is downgraded in quality, loses market value, and may become unfit for human or animal consumption. Studies have shown that rodent infestations can lead to quantitative losses ranging between 2% and 5% annually in grain storage structures. In urban godowns and rural warehouses, this figure can be much higher under unmanaged conditions. Bird infestation in open grain depots may result in 1–2% loss in just a few weeks if no deterrent systems are in place. Beyond the economic cost, the indirect loss due to health hazards and the need for cleaning, repackaging, or disposal adds to the operational burden.

C. Preventive and control strategies (traps, repellents, exclusion)

Preventing rodent and bird infestations requires a combination of physical, mechanical, and environmental control methods. Rodent-proofing of storage structures is the first line of defense, involving construction of barriers, sealing of entry points, and use of metal sheeting around doors and corners. Mechanical traps such as snap traps, glue boards, and live-capture cages are widely used, particularly in small-scale warehouses. Poison baiting with anticoagulant rodenticides like bromadiolone is effective under controlled conditions, but care must be taken to avoid accidental poisoning of non-target organisms and ensure bait placement in tamper-proof stations. For birds, netting and mesh screens prevent entry into godowns, while visual deterrents like reflective strips, scare balloons, and predator models provide short-term relief. Acoustic devices that emit distress calls can be used in urban settings to repel flocks. Habitat management through removal of water sources, grain spills, and nesting materials greatly reduces pest pressure. Sanitation and routine inspection play a key role in detecting early signs of infestation and preventing large-scale damage. Integrated vertebrate pest management, combining exclusion, trapping, repellents, and environmental modification, offers a sustainable approach to protecting stored grains from rodent and bird-related losses.

Quality Standards and Storage Loss Assessments

A. BIS and FSSAI guidelines for grain quality

The Bureau of Indian Standards (BIS) and Food Safety and Standards Authority of India (FSSAI) play a central role in regulating grain quality through detailed specifications related to purity, moisture content, physical contaminants, and permissible levels of biological hazards. BIS prescribes quality norms under IS codes for various food grains, such as IS 4333 for rice and IS 14818 for wheat. These standards define parameters like maximum moisture percentage (typically 12–14% for safe storage), foreign matter limits, damaged grain percentage, and infestation levels. FSSAI, as the apex food safety regulator, stipulates maximum residue limits (MRLs) for pesticides, microbiological safety levels, and mycotoxin thresholds in compliance with international Codex guidelines. For example, FSSAI sets aflatoxin limits at 30 micrograms per kilogram for cereals and pulses. Adherence to these standards ensures food safety for consumers and compliance with domestic and export regulations.

B. Sampling and evaluation methods

Accurate sampling and evaluation are essential for detecting storage losses and maintaining quality standards. The process involves collecting representative grain samples from different sections of a storage unit—top, middle, and bottom layers, as well as around walls and corners. The sample size and method are standardized under BIS protocols to avoid bias. Tools such as triers, grain probes, and compartment samplers are used. Once collected, samples undergo laboratory analysis for moisture content, grain impurities, insect presence, fungal contamination, and germination viability. Physical examination includes counting discolored or damaged kernels, while chemical tests determine mycotoxin content, pesticide residues, and microbial load. Advanced techniques such as near-infrared spectroscopy (NIRS), gas chromatography, and ELISA (enzyme-linked immunosorbent assay) are increasingly applied for faster and more precise analysis. Frequent sampling during the storage cycle enables early detection of quality deterioration and supports timely corrective action.

C. Documentation and traceability in grain quality monitoring

Documenting grain quality parameters and storage conditions is essential for maintaining traceability and ensuring accountability at every stage of the post-harvest supply chain. Grain procurement centers, warehouses, and transporters are expected to maintain records on moisture readings, pest control treatments, inspection schedules, fumigation logs, and pesticide applications. These documents help identify the source and cause of contamination or quality loss and support the implementation of corrective protocols. Traceability is particularly important for export consignments and food aid programs, where strict compliance with international standards is required. Electronic systems for inventory and quality tracking are now integrated with warehouse management software (WMS), allowing for real-time updates on grain quality metrics and storage conditions. QR codes, RFID tags, and blockchain-based systems are emerging technologies that enhance traceability and reduce errors or fraud in grain handling systems. These measures ensure transparency in food supply chains, improve market confidence, and promote better pricing and access for quality-assured produce.

Future Perspectives in Stored Grain Protection

A. Development of bio-safe storage technologies

The transition toward bio-safe storage technologies is gaining momentum due to concerns over pesticide residues, ecological impact, and health risks (Hasan *et.al.,* 2024). Hermetic storage systems, which function through oxygen exclusion, are increasingly being promoted for household- and community-level grain preservation. These include triple-layered Purdue Improved Crop Storage (PICS) bags and ZeroFly storage bags, which prevent insect development without the use of chemicals. Scientific evaluations have demonstrated that hermetic systems can suppress major stored grain pests such as *Sitophilus oryzae* and *Tribolium castaneum* by limiting oxygen to below 3%, thus halting their metabolic activity. Biofumigants such as neem-based formulations, essential oils (e.g., eucalyptus, clove), and plant powders (e.g., sweet flag, turmeric) are also showing promise as alternatives to conventional synthetic fumigants like aluminum phosphide. Biological control agents such as Bacillus thuringiensis and entomopathogenic fungi like Beauveria bassiana are under evaluation for long-term application in enclosed grain storage systems, combining safety with efficacy.

B. Use of digital sensors and IoT-based monitoring

Advances in sensor technology and Internet of Things (IoT) platforms are revolutionizing grain storage management through real-time data tracking and predictive analytics. Digital grain probes equipped with sensors monitor temperature, relative humidity, and carbon dioxide concentration within bins or silos. These data points are transmitted wirelessly to cloud-based platforms for continuous analysis. When thresholds indicating pest activity or spoilage risk are exceeded, automated alerts are generated, allowing for timely intervention. Smart storage bins integrated with IoT systems can reduce insect infestation rates by 30–40% and minimize the risk of mold growth through automated aeration or dehumidification. Machine learning models trained on historical storage data can forecast hotspots for pest development or grain degradation. By shifting from reactive to predictive management, these technologies offer significant improvements in both quality retention and operational efficiency. Pilot studies in university research stations and select farmer producer organizations have shown promising reductions in spoilage, shrinkage, and mycotoxin levels under sensor-assisted storage regimes.

C. Public-private initiatives in reducing post-harvest losses

Collaborative frameworks between public institutions, private companies, and farmer groups are playing a transformative role in tackling post-harvest grain losses. National-level programs such as the Rashtriya Krishi Vikas Yojana and the PM Formalization of Micro Food Processing Enterprises (PM-FME) scheme are allocating resources toward improving rural storage infrastructure and post-harvest handling practices. Private firms involved in grain storage logistics are investing in large-scale steel silos, cold chains for oilseeds, and climate-resilient godown technologies under build-operate-transfer (BOT) models. Public sector research organizations and agricultural universities are partnering with agritech startups to develop low-cost moisture meters, mobile apps for pest identification, and farmer-friendly training modules. These efforts are supported by international agencies such as FAO, World Bank, and USAID, which emphasize value chain strengthening and food security enhancement. Impact assessments of such initiatives have shown a potential to reduce post-harvest grain losses by 10–15% in targeted clusters, improve farm gate prices, and enhance export readiness by ensuring compliance with global quality standards.

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Chapter 9

Rodents, Birds, and Microbial Threats in Grain Storage

Surendra Prasad*[1], Surekha Kamlesh Kurankar[2] and Priya Kashyap[3]

[1]*Assistant Professor, Department of Entomology, PGCA, Dr Rajendra Prasad Central Agricultural University Pusa, Bihar*

[2]*Assistant Professor, Department of Zoology, R C PATEL Arts Commerce and Science College Shirpur*

[3]*Zoology, Entomology, CCSU, Meerut College Meerut*

***Corresponding Author Email:** sprasad@rpcau.ac.in

The protection of stored grain is not solely dependent on the control of insect pests; non-insect threats such as rodents, birds, and microbes pose equally serious risks. These pests contribute significantly to both direct and indirect losses during post-harvest storage. Rodents gnaw through packaging and structural materials, birds peck and scatter grains, and microbes like fungi and bacteria contaminate food commodities, rendering them unfit for consumption or processing. These agents often work synergistically rodent and bird activity facilitates microbial entry, while microbial spoilage may attract secondary pests. As grain storage is a critical component of the food supply chain, any compromise in its integrity can lead to reduced food security, economic loss to producers and traders, and increased risk of public health hazards. Preventing losses from non-insect threats is essential for ensuring the safety, quality, and sustainability of stored agricultural produce.

B. Economic and qualitative losses due to rodents, birds, and microbes

Losses from non-insect pests are multifaceted. Rodents alone are estimated to consume up to 3–5% of stored grains annually in unmanaged facilities, with an even greater percentage lost due to contamination by droppings, urine, and hair. Each rat may consume between 15 to 25 grams of food per day while contaminating several times that amount. Birds such as house sparrows and crows can cause up to 1–2% loss in exposed storage or during drying periods, with fecal contamination increasing the microbial load. Microbial agents, particularly fungi like Aspergillus flavus and Penicillium spp., contribute to severe quality deterioration by producing mycotoxins such as aflatoxins and ochratoxins, which are carcinogenic and often lead to rejection of grain shipments in domestic and international markets. Bacteria like Salmonella and Bacillus spp. can cause food poisoning and spoilage, especially under humid conditions. These non-insect threats collectively reduce nutritional value, seed germination rates, and shelf-life of grains, while increasing food safety risks and market rejection rates.

C. Importance of integrated management in grain storage biosecurity

An integrated approach is necessary to mitigate the complex risks posed by rodents, birds, and microbial contaminants in storage systems (Gomes *et.al.,* 2023). Single control methods are often insufficient, as these threats operate through diverse modes of action mechanical damage, biological contamination, and environmental manipulation. Integrated management includes a combination of physical barriers, regular sanitation, biological interventions, and chemical measures aligned with safety guidelines. Biosecurity in grain storage also involves infrastructure design, monitoring protocols, pest-proofing techniques, and regulatory compliance to reduce the ingress and spread of harmful agents. The goal is not only to control existing threats but to create conditions that prevent their establishment. With rising demand for safe, residue-free food and increasing awareness of post-harvest losses, integrating non-insect pest management into grain storage strategies has become essential for food preservation, economic viability, and public health assurance.

Rodent Pests in Grain Storage

A. Common rodent species in storage environments

Grain storage systems are frequently threatened by the activity of three dominant rodent species that have adapted to live in close association with human environments. Rattus rattus, commonly known as the roof rat, is a highly agile species that prefers elevated structures like rafters, beams, and high shelves. It is slender, with a long tail and large ears, and is particularly destructive in warehouses and granaries due to its climbing ability and voracious appetite. Mus musculus, or the common house mouse, is smaller and more adaptable, occupying both urban and rural storage areas. Its high reproductive rate and secretive behavior allow populations to grow rapidly in concealed spaces. Bandicota bengalensis, known as the lesser bandicoot rat, is a ground-dwelling rodent that is particularly destructive due to its burrowing activity. It creates extensive tunnel systems around storage structures, undermining foundations and creating entry routes for other pests.

B. Identification and behavioral characteristics

Rodents active in grain storage areas are primarily nocturnal, conducting most of their feeding, nesting, and exploratory behavior during the night. They are compulsive gnawers, with continuously growing incisors that drive them to chew on wood, plastic, fabric, and electrical wiring. This gnawing behavior causes significant structural damage, often leading to short circuits or container breaches. Burrowing activity, particularly by bandicoots, results in weakened floors and provides hidden passages that facilitate infestation. Reproduction is rapid and continuous in the presence of abundant food and shelter. A single female *Rattus rattus* can produce 5 to 6 litters per year, with 6 to 12 pups per litter. Gestation lasts around 21 to 24 days, and the young reach sexual maturity within 2 to 3 months.

This reproductive capacity enables rodent populations to explode under favorable conditions, making early detection and control essential.

C. Nature and extent of damage

Rodents cause both direct and indirect damage to stored grains. Directly, they consume a substantial quantity of grain an adult rat may eat 15 to 25 grams daily. Across a storage season, this consumption can translate to several kilograms of loss per rodent. Indirect damage includes contamination through urine, feces, saliva, and hairs, which render grain unfit for human consumption and may spread bacterial pathogens such as *Salmonella*. The presence of contaminated grains in storage leads to rejection in quality assessments and loss of market value. Rodents also cause physical damage to bags, sacks, and packaging materials, leading to grain spillage and easier access for insect pests. Their burrowing undermines storage foundations, and their gnawing of doors and insulation reduces the integrity of sealed or temperature-regulated environments. Cumulatively, these factors result in substantial economic and hygienic losses.

D. Monitoring rodent presence

Effective rodent management begins with systematic monitoring. Signs of activity include fresh droppings, which vary in size and shape based on the species. Gnaw marks on wood, plastic, and sacks are early indicators, as are greasy rub marks along walls and floors created by rodent fur. Footprints and tail drag marks in dusted areas can reveal movement patterns. Urine stains become visible under ultraviolet light, providing further evidence of rodent pathways. Bait stations, both toxic and non-toxic, are used to assess rodent presence and feeding activity. Mechanical traps serve as both surveillance tools and control measures. The placement of traps along known runways, near burrow openings, and behind stacks helps in estimating population density and guiding further intervention. Frequent inspection of these monitoring tools enables early detection and containment before populations escalate.

E. Rodent control strategies

Prevention is the cornerstone of rodent management. Structural sanitation such as cleaning spills, removing waste, and sealing cracks and holes in walls and floors denies rodents access to food and shelter. Entry points should be blocked using metal sheeting or concrete barriers, especially around drainage pipes and doors. Mechanical control methods include snap traps, glue boards, and live traps, which are suitable for small infestations and sensitive environments. These devices should be used strategically, accompanied by regular inspection and relocation. Chemical control through rodenticides is widely practiced. Acute poisons such as zinc phosphide offer quick kill effects, while anticoagulants like bromadiolone and warfarin work through repeated exposure and internal hemorrhaging. These rodenticides are delivered through bait formulations and must be placed securely to avoid non-target exposure.

Biological control is under active research, with some promising results. Predators such as owls and snakes naturally suppress rodent populations in agricultural zones. Research into rodent-specific pathogens and fertility-inhibiting agents continues, with the aim of offering environmentally safe alternatives. Rodent-proof storage design is also a long-term preventive measure. This includes the use of metallic grain bins with tight-fitting lids, elevated platforms for bag storage, and rodent barriers around entry points. Layouts should allow for visual inspection and easy cleaning. Proper lighting and elimination of clutter discourage rodent harboring. By integrating these control measures into storage management protocols, long-term grain security and hygiene can be achieved.

Bird Pests in Storage and Processing Units

A. Common bird species affecting grain storage

Birds pose a persistent challenge to grain storage and processing facilities, particularly in semi-open or poorly secured units (Sharma *et.al.,* 2023). Among the most frequently encountered species are Ploceus philippinus (Baya weaver), Passer domesticus (House sparrow), and Corvus splendens (House crow). The Baya weaver is a seed-eating bird that typically nests in nearby trees or structures and often invades storage yards during the day to feed on exposed grains. The House sparrow, although small, enters storages through minor openings and causes localized but continuous losses due to its familiarity with human environments. The House crow, a larger and more aggressive species, not only feeds on grains but also scavenges for discarded food and waste around storage facilities. These birds are highly adaptive, learn to exploit human-modified environments quickly, and often congregate in large numbers, escalating the potential for grain damage and contamination.

B. Behavior and feeding habits

Birds that invade grain storage systems are largely diurnal and show peak activity during early morning and late afternoon. Their feeding is opportunistic, and they are attracted to easily accessible grain heaps, drying platforms, and loosely packed or torn storage bags. Communal roosting is common, especially near human settlements and food handling areas. Such behavior allows large numbers of birds to feed in a single area, increasing the impact on stored products. These birds exhibit high site fidelity, returning to the same feeding sites daily unless disturbed. Their persistence and ability to access grain through small openings or broken structures make them particularly difficult to exclude without proper preventive infrastructure. Their droppings, feathers, and nesting materials also accumulate rapidly in open storage environments.

C. Nature of damage caused by birds

Birds cause both quantitative and qualitative damage to stored and processed grains. Pecking directly reduces the quantity of saleable grain, particularly in drying yards, hulling units, or open packaging stations. Grain spillage from disturbed containers and sacks is common, and partial grain consumption often results in downgrading of the product. Bird droppings contain high levels of uric acid and serve as vectors for bacteria and fungi, such as Salmonella and Aspergillus species. This leads to chemical contamination, spoilage, and potential health hazards for both consumers and workers. Physical contamination with feathers, nest debris, and excreta reduces the aesthetic and hygienic quality of food grains and may lead to rejection in food safety inspections. Birds also interfere with post-harvest activities by disrupting packaging operations and nesting in storage racks, ducts, and ventilation systems, often clogging them and posing fire hazards in grain dryers.

D. Bird control methods

Effective bird management in storage and processing facilities requires a multi-pronged strategy combining exclusion, deterrence, and habitat alteration. Structural barriers such as polyethylene netting, galvanized iron wire mesh, and translucent sheets are installed across open doors, windows, and air vents to prevent bird entry. These barriers are durable and suitable for warehouses and grain drying yards. Visual and acoustic deterrents are also commonly used. Traditional scarecrows, reflective strips, predator-shaped balloons, and rotating mirrors create visual disturbance. Sound-based repellents, including recorded distress calls or ultrasonic devices, are used to interfere with bird communication and discourage repeated visits. Such deterrents are most effective when frequently repositioned to avoid habituation.

Habitat modification involves altering the surroundings to make the area less attractive for roosting and feeding. Removing nearby nests, trimming tree canopies, and covering grain piles reduce the incentive for birds to remain in the area. Avoiding food spills, cleaning waste bins, and controlling garbage around storage zones further discourage bird congregation. Regulatory frameworks often prohibit the use of lethal control methods due to the protected status of many bird species under wildlife conservation laws. This necessitates a reliance on non-lethal, environmentally responsible methods. Integrated bird management ensures compliance with food safety regulations while maintaining hygiene and minimizing grain losses during storage and handling operations.

Fungal Threats in Stored Grain

A. Major storage fungi

Fungal contamination is a significant challenge in grain storage, especially under warm and humid conditions that prevail across various storage environments. Among the most commonly encountered storage fungi are Aspergillus flavus, Aspergillus niger, Penicillium species, and Fusarium species. Aspergillus flavus is particularly notorious due to its ability to produce aflatoxins, a class of potent carcinogenic mycotoxins that affect human and animal health. It typically colonizes oilseeds, maize, groundnuts, and cereals under high humidity. Aspergillus niger is commonly found in high-moisture cereals and legumes, contributing to black mold and spoilage. Penicillium spp. dominate in cooler climates and cause blue-green mold, particularly in wheat and barley, while also producing ochratoxins harmful to kidneys. Fusarium spp., often introduced from field infection, persist in storage and can produce trichothecenes and fumonisins, mycotoxins with severe toxic effects. These fungi reduce the aesthetic, nutritional, and commercial value of stored grains and are major causes of rejection in food safety assessments globally.

B. Conditions favoring fungal growth

Fungal proliferation in stored grains is driven by several interrelated factors. High moisture content, typically above 14%, is the most critical factor that enables fungal spores to germinate and colonize grain surfaces. Moist grains provide an ideal substrate for fungal respiration and enzymatic degradation. Poor aeration and lack of proper ventilation result in the formation of localized hotspots within the storage bulk, raising both temperature and humidity levels. Such microenvironments create condensation, allowing fungi like Aspergillus and Penicillium to thrive. Damaged grains, broken kernels, and the presence of foreign material such as husks and chaff serve as initial sites for fungal invasion, as these surfaces are easier for hyphal penetration. Impurities also interfere with airflow, encouraging moisture retention. When coupled with improper handling and infrequent inspection, these conditions can lead to widespread contamination and spoilage within a short span of time.

C. Impact of fungal contamination

The effects of fungal invasion in stored grain are severe and multifaceted. Initial signs include grain discoloration, the development of a musty odor, and surface spoilage (Sha *et.al.,* 2025). This physical deterioration is often accompanied by clumping and caking of grains, which complicates handling and processing. The nutritional quality of the grain declines significantly due to fungal metabolism consuming carbohydrates, proteins, and lipids. For seed lots, viability and germination rates drop sharply, often rendering them unusable for the next planting season. The most serious consequence arises from mycotoxin production. *Aspergillus flavus* produces aflatoxins B1 and B2, known to cause liver damage and immune suppression. *Penicillium* and *Fusarium* species produce ochratoxins and fumonisins respectively, which are nephrotoxic and neurotoxic. These mycotoxins can survive processing and cooking, making them persistent risks in food chains. International trade regulations, such as those enforced by the Codex Alimentarius and European Union, place strict limits on acceptable mycotoxin levels, often resulting in the rejection of contaminated grain shipments. This not only causes financial losses but also damages market reputation and food safety credibility.

D. Fungal control strategies

Managing fungal threats in stored grain requires a combination of preventive and corrective measures rooted in scientific understanding. The first and most essential step is thorough drying of grains to a safe moisture level below 12%, using sun drying or mechanical dryers. This deprives fungi of the water activity necessary for growth. Proper aeration systems, especially in bulk storage silos and warehouses, help in maintaining uniform temperature and humidity. This includes the use of forced-air ventilation, exhaust fans, and aeration ducts to prevent condensation. The application of antifungal agents, such as propionic acid and sodium benzoate, provides chemical protection when used in accordance with safety standards. Botanical products like neem leaf powder and clove oil are gaining popularity as natural antifungals with lower residue concerns. Regular monitoring through moisture meters, grain sampling, and microbial testing allows early detection of fungal activity. Periodic laboratory analysis for mycotoxin residues ensures compliance with food safety standards. Implementing these strategies collectively ensures that fungal contamination is minimized, preserving grain quality, food safety, and economic value during extended storage periods.

Bacterial Contamination in Storage

A. Common bacterial species in stored grain environments

Bacterial contamination, although often overshadowed by fungal threats, poses a significant risk to the safety, quality, and marketability of stored grain. Among the most frequently identified bacterial genera in grain storage systems are Bacillus, Pseudomonas, and Salmonella. Bacillus spp. are spore-forming bacteria that survive harsh storage conditions and may proliferate under elevated moisture and temperature, leading to spoilage and discoloration. Some species like Bacillus cereus are known to produce enterotoxins, causing foodborne illness when consumed. Pseudomonas spp.are aerobic, psychrotolerant bacteria that colonize moist environments and contribute to odor development and discoloration, especially in high-moisture grains. The presence of Salmonella spp. is of particular concern in food safety surveillance. These pathogens are capable of surviving in dry environments and are commonly associated with contamination from rodent feces, bird droppings, or unclean storage conditions. They represent a direct risk to human health due to their link to salmonellosis, a condition marked by gastrointestinal illness and severe complications in immunocompromised individuals.

B. Sources and spread of bacterial contamination

The entry and proliferation of bacteria in stored grain are closely linked to lapses in hygiene and environmental control. Improper handling practices during harvest, drying, and loading such as the use of unclean tools or contaminated bags can introduce bacterial inoculum onto the grain surface. In storage, bacteria are spread through exposure to contaminated surfaces, equipment, and pests. Rodent and bird droppings are primary vectors for transmitting Salmonella and E. coli, contaminating both grain and structural surfaces. Moisture buildup due to inadequate drying or water seepage creates favorable microenvironments that promote bacterial multiplication. Bacteria thrive in residues of broken grains, organic debris, and moldy patches, where they form biofilms and persist over extended periods. Poor sanitation, absence of regular cleaning schedules, and lack of pest exclusion measures accelerate the spread of bacterial populations across the storage environment.

C. Effects of bacterial presence in grain

The presence of bacteria in stored grain results in both visible and invisible damage. Spoilage symptoms include the production of foul or musty odors, sticky grain masses, and discolored patches that reduce commercial value and consumer acceptance. Some bacteria degrade grain nutrients, leading to loss of energy value, protein quality, and germination potential. From a food safety perspective, bacterial contamination is a major cause for concern, especially in export-oriented or processed grain sectors. Contaminated grains can lead to rejection by regulatory agencies, loss of certifications, and recalls in the food industry. Pathogenic bacteria such as Salmonella and Listeria monocytogenes pose a direct threat to consumers, and their detection often results in trade restrictions and legal consequences. Cross-contamination during processing is another critical issue. Equipment used in milling, packaging, or transport can become contaminated and spread bacteria to clean batches, perpetuating the cycle of contamination throughout the supply chain.

D. Prevention and management

Mitigation of bacterial contamination in grain storage requires a robust hygiene framework, infrastructure design, and regular monitoring (Mahunu *et.al.,* 2024). Sanitation of storage infrastructure is fundamental and must include cleaning and disinfection of floors, walls, silos, and storage bins before every filling cycle. Tools, conveyor belts, and packaging materials should be sterilized or sanitized with food-safe agents. The use of approved disinfectants such as chlorine-based or quaternary ammonium compounds can help in eliminating bacterial residues on surfaces.

Cleaning protocols should follow a documented schedule with assigned personnel and checklists to ensure accountability.

Regular microbial testing of grain samples and surface swabs enables early detection of bacterial colonies. These tests include standard plate counts, specific pathogen detection assays, and moisture monitoring to ensure conditions remain below thresholds conducive to microbial growth. Safety audits, conducted periodically, reinforce best practices and identify potential lapses in handling or infrastructure maintenance. A comprehensive record of microbial surveillance, cleaning operations, and corrective actions supports compliance with food safety regulations such as those under FSSAI and international standards like HACCP and Codex. Proactive management of bacterial risks ensures that stored grain remains safe for consumption, processing, and trade while preserving its quality and market value.

Integrated Management of Non-Insect Pests

A. Principles of integrated non-insect pest management

The management of non-insect pests in grain storage such as rodents, birds, fungi, and bacteria requires an integrated approach that emphasizes prevention, early detection, and sustainable control methods. The foundation of integrated non-insect pest management (INPM) lies in a proactive strategy that combines multiple compatible control techniques, reduces dependence on synthetic chemicals, and prioritizes long-term efficacy. Key principles include habitat modification to make storage environments less conducive to pests, exclusion techniques to block entry routes, biological interventions where possible, and the judicious use of chemical controls only when necessary. An effective INPM plan is dynamic and adaptable to changing pest pressures, environmental conditions, and storage durations.

B. Combining cultural, mechanical, biological, and chemical approaches

The success of INPM depends on the coordinated application of various pest control methods, each contributing to a different aspect of pest suppression. Cultural practices form the first line of defense, emphasizing hygiene, sanitation, timely harvesting, and adequate drying of grains to below 12% moisture, which inhibits microbial and fungal growth. Cleaning of storage structures and equipment prevents residue buildup that supports pest survival. Mechanical methods such as rodent traps, bird netting, and grain sifters serve to physically remove or exclude non-insect pests from stored grain systems. Structures designed with rodent-proof construction and proper ventilation further enhance protection.

Biological control, while more developed for insect pests, is gaining ground for non-insect threats. Predators such as barn owls contribute to rodent suppression, while entomopathogenic fungi and microbial antagonists are being explored for suppressing storage fungi and bacteria. Plant-based repellents such as neem leaves and mustard oil, traditionally used to deter both microbial growth and rodent activity, provide an eco-friendly complement to other control methods. Chemical measures are used selectively, typically as corrective tools. Rodenticides, antifungal agents, and disinfectants must be applied with caution, respecting safety thresholds and storage residue regulations. Their use must follow prescribed application techniques, withholding periods, and documentation to avoid contamination of food grains.

C. Role of trained personnel and stakeholder participation

Implementation of INPM requires involvement from trained personnel across all levels of the storage and supply chain. From warehouse managers to farmers and transport handlers, every stakeholder must understand the risks posed by non-insect pests and their control methods. Training programs on pest identification, sanitation protocols, fumigation procedures, and hygiene compliance strengthen the overall capacity to manage threats. Extension services, cooperatives, and food safety authorities play a central role in transferring this knowledge and encouraging the adoption of integrated practices. Effective communication and collaboration among storage operators, food processors, and regulatory agencies ensure that pest control measures are standardized, verified, and enforced.

D. Monitoring systems and record keeping

A critical component of INPM is the establishment of robust monitoring systems that detect pest activity before it leads to substantial damage. Regular inspection schedules must be followed for signs of rodent, bird, and microbial infestation. Tools such as bait stations, sticky traps, temperature and moisture sensors, and UV lamps help identify activity levels and sources of contamination. Grain sampling for microbial testing, especially for fungal spores and bacteria like Salmonella, provides quantitative data to guide intervention decisions. Detailed records must be maintained on storage conditions, inspection results, pest sightings, control actions taken, and chemical applications. This data is essential for audits, quality certification, and continuous improvement of pest management protocols.

E. Cost-benefit analysis of preventive vs. curative measures

Preventive strategies in INPM are generally more cost-effective than reactive or curative actions. The initial investment in sanitation infrastructure, pest-proof storage, and training yields long-term benefits by reducing the frequency and severity of infestations. Preventive actions also avoid grain losses, quality degradation, and the costs associated with rejected consignments. Curative measures such as chemical treatments, while sometimes necessary, involve higher expenses, labor, and safety risks, particularly during fumigation or disinfection. Delayed intervention may result in irreversible contamination or spoilage, leading to complete loss of stored grain. A well-designed INPM program evaluates the financial trade-offs between up-front investment in preventive tools and the potential costs of pest outbreaks, always aiming for sustainable and economically viable outcomes. Integrated non-insect pest management, by leveraging multidisciplinary tools and stakeholder coordination, ensures safer storage, improved grain quality, and enhanced food security.

Government Regulations and Standards

A. Guidelines from FCI, CWC, and State Warehousing Corporations

The Food Corporation of India (FCI), Central Warehousing Corporation (CWC), and various State Warehousing Corporations (SWCs) play critical roles in establishing and enforcing quality and safety protocols for stored grains. These agencies are responsible for managing large-scale public food reserves and ensuring that stored grains meet national food security and distribution standards. FCI maintains a comprehensive system for procurement, storage, and distribution, adhering to scientific storage practices that minimize losses due to rodents, birds, and microbial threats. Warehouses under CWC and SWCs are required to comply with structural norms that include rodent-proofing, aeration systems, fumigation readiness, and sanitation protocols. Storage premises are subject to regular audits, and standard operating procedures are in place for cleaning schedules, pest surveillance, and corrective actions. These organizations also promote training programs for warehouse managers and staff to ensure awareness of non-insect pest management and hygiene control practices.

B. BIS and FSSAI safety thresholds for microbial and rodent contamination

The Bureau of Indian Standards (BIS) and the Food Safety and Standards Authority of India (FSSAI) set mandatory guidelines regarding acceptable contamination levels in stored grains (Reddy *et.al.,* 2017). BIS prescribes quality grades for various food grains under IS codes, which define the permissible limits for damaged grains, foreign matter, moisture, and infestation. Any evidence of rodent activity or microbial spoilage results in downgrading or outright rejection of grain consignments. FSSAI, as the apex food regulatory body, enforces microbial safety standards for food products under its Food Safety and Standards (Food Products Standards and Food Additives) Regulations. These include maximum permissible limits for Salmonella spp., Bacillus cereus, Escherichia coli, and mycotoxins such as aflatoxins and ochratoxins. Stored grains exceeding these thresholds are deemed unfit for human consumption. The presence of rodent feces, hair, or urine in food commodities violates both BIS and FSSAI criteria and attracts regulatory penalties.

C. Compliance protocols for export and domestic supply chains

Grain storage systems linked to export and domestic distribution must follow strict compliance protocols to meet national and international quality benchmarks. Export-bound consignments are subject to phytosanitary inspections, which include tests for microbial contamination, rodent presence, and structural pest resistance. Countries importing agricultural commodities demand certification under global standards such as Codex Alimentarius, ISO 22000, and HACCP (Hazard Analysis and Critical Control Points). To ensure compliance, exporters must maintain records of fumigation, grain conditioning, warehouse sanitation, and pest control measures. Domestic supply chains under public distribution or private retail channels require traceability of storage practices, with audit trails covering moisture content, microbial test reports, and pest management logs. Government agencies monitor these supply chains through routine sampling, laboratory analysis, and enforcement of food safety licenses. Facilities failing to meet standards risk suspension of operations, blacklisting, or fines. Effective adherence to these protocols ensures food safety, supports trade credibility, and protects public health across all levels of grain handling and distribution.

Case Studies and Best Practices

A. Successful rodent-proof godown design examples

One notable example of rodent-proof storage design is the use of reinforced concrete godowns with elevated platforms and metallic skirting around door frames and vents (Timm *et.al.,* 1983). These designs prevent rodent entry by eliminating burrowing routes and gnawing access points. In several public sector facilities operated by warehousing corporations, godowns have been upgraded with metal baffles on pipelines, sealed expansion joints, and tight-fitting doors with rubber gaskets. The grain stacks are arranged on wooden or plastic pallets with a one-meter perimeter clearance to facilitate monitoring and cleaning. Lighting is strategically placed to reduce dark hiding zones. Such modifications, combined with regular inspection and trap-based surveillance, have reduced rodent infestation to near-zero levels in these storage sites over five-year periods. Reports from these facilities show a significant decrease in grain loss, improved hygiene ratings, and lower dependency on chemical rodenticides.

B. Case reports of aflatoxin contamination and control

Aflatoxin contamination, primarily caused by Aspergillus flavus, has led to serious losses in groundnut and maize consignments. A detailed study conducted during a warehouse monitoring project showed that grain batches stored with moisture levels above 14.5% had aflatoxin levels exceeding 20 ppb, the maximum threshold accepted by many export markets. After this incident, corrective steps were introduced, including the adoption of mechanical grain dryers to lower moisture content to 11%, the use of breathable jute sacks over plastic, and weekly aeration cycles in bulk silos. Neem-based antifungal treatments and phosphine fumigation were tested, with neem powder showing significant inhibition of fungal growth in storage trials lasting six months. Post-intervention reports documented a drop in aflatoxin levels to below 5 ppb, with no additional microbial contamination detected. This case demonstrated that proper moisture management and botanical-based prevention can effectively limit toxin-producing fungal threats.

C. Community-led bird deterrent programs

In a district cooperative storage facility dealing with paddy and wheat, bird-related losses had escalated due to open drying areas and loosely covered stacks. Local farmer groups collaborated with warehouse managers to implement a bird deterrence initiative. This included the installation of nylon mesh screens, predator-shaped balloons, and motion-activated reflective tapes. Children from nearby schools painted predator murals around the periphery, creating a consistent visual disturbance. Noise devices using repurposed tin sheets were deployed during peak bird activity hours. Grain spillage was minimized by enforcing strict bagging protocols and using tarpaulins during transport. Within a single harvest cycle, observations showed a 70% reduction in bird presence and measurable improvement in grain cleanliness. The success of this community-involved model highlighted the role of collective action and low-cost solutions in enhancing storage hygiene.

D. Documentation of integrated storage hygiene models

An integrated hygiene protocol implemented at a government-managed food storage depot demonstrated substantial gains in both quality maintenance and pest reduction (Rankin *et.al.,* 2016). The model included a combination of pre-storage sanitation, routine floor cleaning, air circulation through forced ventilation, pest-proof stacking, and moisture monitoring. Each of the operational areas was color-coded for sanitation tasks, with dedicated teams responsible for rodent control, microbial testing, and structural inspection. Detailed logs of each operation, including pesticide application, were maintained and reviewed weekly. The site achieved ISO 22000 certification after compliance with hazard analysis and critical control points (HACCP) was verified. Within two years, the depot reported a 30% drop in overall post-harvest losses, with microbial counts and rodent indicators remaining consistently below acceptable thresholds. This case stands as a replicable model for large-scale storage institutions aiming to implement food safety and biosecurity without heavy reliance on chemical treatments.

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Chapter 10

Non-Insect Pests: Mites, Snails, and Slugs

Shruti Biradar*[1], Satappa Kharbade[2] and Aishwarya Chavan[3]

[1]Ph.D. Scholar, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri

[2]Professor, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri

[3]Ph.D. Scholar, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri

***Corresponding Author Email:** shrutibiradar137@gmail.com

Non-insect pests are organisms that are not classified under the class Insecta but still cause significant damage to crops, stored products, and horticultural systems. These pests include various arthropods such as mites (belonging to the subclass Acari) and molluscs like snails and slugs. Unlike typical insect pests that have segmented bodies and three distinct body parts (head, thorax, and abdomen), non-insect pests may have unsegmented or differently segmented bodies, different developmental biology, and feeding behaviors. These organisms often go unnoticed in early infestation stages but can become destructive when populations increase rapidly.

A. Significance in agriculture

Non-insect pests play a substantial role in reducing agricultural productivity. Mites, for example, affect both field crops and horticultural plants by feeding on plant sap, which results in reduced photosynthesis, stunted growth, and leaf necrosis. Slugs and snails consume a variety of plant tissues, from leaves and stems to fruits and roots. Their feeding activity is especially damaging to young seedlings and soft-tissue vegetables. These pests also create entry points for pathogens, indirectly causing plant diseases. Effective management of non-insect pests is crucial to maintaining plant health, ensuring crop quality, and achieving sustainable agricultural outcomes.

B. Major non-insect pests: mites, snails, and slugs

The most commonly encountered non-insect pests in agriculture include mites, snails, and slugs. Mites, such as the two-spotted spider mite (*Tetranychus urticae*), are tiny arachnids that feed on plant cells by piercing leaf tissues. They reproduce rapidly under warm and dry conditions and can complete their life cycle in less than a week during favorable periods. Snails and slugs, classified under the class

Gastropoda, are soft-bodied molluscs. Snails possess a coiled shell, while slugs lack a visible external shell (Heller *et.al.,* 2015). Both groups are highly destructive in moist environments, especially during monsoon and post-irrigation periods, and are capable of decimating crop seedlings overnight.

C. Economic and ecological impact on crop production

Non-insect pests contribute significantly to crop losses globally. Mite infestations in vegetable crops like tomato, chili, and eggplant can reduce yields by up to 40% under severe outbreaks. In tea plantations, red spider mites can affect up to 60% of leaf surfaces, directly impacting the quality of the processed product. Molluscs such as the giant African snail (Achatina fulica) have been identified as major pests in banana, papaya, and leafy vegetables, with feeding damage reaching 30–50% yield loss during peak infestation periods. Beyond yield losses, these pests increase production costs due to the need for repeated interventions and pest monitoring. Ecologically, molluscs can outcompete native species, disrupt soil ecosystems, and act as intermediate hosts for parasites affecting humans and livestock. Control strategies must, therefore, balance efficacy with ecological sustainability to minimize unintended consequences.

Mites

A. Classification and Identification

1. Taxonomic position (Acari: Arachnida)

Mites belong to the subclass Acari under the class Arachnida, which places them in the same group as spiders, ticks, and scorpions. Unlike insects, which have three body segments and six legs, mites have two main body regions (gnathosoma and idiosoma) and four pairs of legs in their nymph and adult stages. This classification allows mites to be distinguished from true insects and highlights their unique physiological and ecological traits.

2. Common families affecting crops (Tetranychidae, Eriophyidae, Tarsonemidae)

Among the Acari, three families are of primary concern in agriculture. The Tetranychidae family, commonly known as spider mites, includes species like *Tetranychus urticae* which are notorious for their web-spinning and rapid reproduction. The Eriophyidae family comprises minute, worm-like mites such as Aceria guerreronis, the coconut mite, which invade concealed plant tissues. The Tarsonemidae family includes mites such as Polyphagotarsonemus latus, which are pests of crops like chili and tea and are known for causing curling and bronzing of leaves.

B. Morphological Characteristics

1. Body structure and size

Mites are extremely small, typically measuring between 0.2 to 0.5 mm, though some species can be slightly larger. They have a soft, unsegmented body, often oval or pear-shaped. Their size and translucent bodies make them difficult to detect without magnification. Most plant-feeding mites possess specialized piercing mouthparts called chelicerae that allow them to feed on cell contents by puncturing the plant epidermis.

2. Differences from insects

Unlike insects, which have three body segments and compound eyes, mites have a fused cephalothorax and abdomen, simple eyes (if any), and no wings or antennae. They possess four pairs of legs as nymphs and adults, compared to the three pairs found in insects. These differences are critical in identifying mites correctly and understanding their movement, feeding, and reproductive behaviors.

C. Biology and Life Cycle

1. Developmental stages: egg, larva, nymph, adult

Mites undergo incomplete metamorphosis. The typical life cycle includes the egg, larva (with three pairs of legs), protonymph, deutonymph, and adult stages. Under optimal temperature and humidity conditions, the entire life cycle may be completed within 7 to 10 days, allowing for rapid population growth. Multiple overlapping generations occur throughout the growing season.

2. Reproductive strategies (parthenogenesis, sexual reproduction)

Many mite species reproduce sexually, but some, such as spider mites, are capable of parthenogenesis. In these cases, unfertilized eggs can develop into males, while fertilized eggs produce females. This reproductive flexibility contributes to their ability to establish populations quickly, even when only a few individuals are initially present.

3. Environmental factors affecting development

Temperature and humidity are the primary environmental factors influencing mite development (Perring *et.al.,* 1984). Warm and dry conditions generally favor faster development and higher reproduction rates. Spider mites thrive in temperatures between 27°C to 30°C and relative humidity below 50%. On the other hand, excessively wet conditions can suppress mite activity by promoting pathogenic fungi and washing off their eggs and webbing.

D. Symptoms of Infestation

1. Leaf discoloration and stippling

One of the earliest signs of mite infestation is a stippled or speckled appearance on leaves, resulting from the removal of chlorophyll-containing cell contents. This leads to a general yellowing or bronzing of the foliage, reducing photosynthetic efficiency and weakening the plant.

2. Webbing on leaves

Spider mites, especially *Tetranychus urticae*, produce fine silk webbing that covers leaf surfaces, stems, and sometimes fruits. This webbing offers protection against natural enemies and chemical sprays, making infestations harder to manage once established.

3. Distorted growth in plants

Infestation by eriophyid and tarsonemid mites often leads to severe physiological changes in plants. These include leaf curling, stunting, blossom drop, and malformed fruits. Polyphagotarsonemus latus causes leaf curling and bronze discoloration in chili, while Aceria guerreronis damages coconut fruits by feeding under the perianth, resulting in poor nut development and husk splitting.

E. Common Mite Pests in Agriculture

1. Red spider mite (Tetranychus urticae)

Tetranychus urticae, also known as the two-spotted spider mite, is a cosmopolitan pest affecting over 200 plant species. It feeds on the undersides of leaves, causing chlorosis and defoliation. Its rapid life cycle and high resistance to pesticides make it one of the most challenging mite pests to control. Yield losses of up to 50% have been reported in crops such as beans, strawberries, and tomatoes.

2. Coconut mite (Aceria guerreronis)

Aceria guerreronis is a serious pest of coconut plantations. It feeds beneath the bracts of young coconuts, causing brownish lesions, nut distortion, and premature nut fall. Infestation levels of over 90% have been observed in some coastal coconut-growing regions. The pest can reduce copra yield by 30–40% if left unmanaged.

3. Citrus rust mite (Phyllocoptruta oleivora)

Phyllocoptruta oleivora is a major pest of citrus crops, particularly oranges and lemons. It attacks fruit surfaces, causing silvering and scarring that reduce market value. Although small in size, heavy populations can damage 60% or more of the fruit surface area, leading to significant post-harvest losses.

F. Management Strategies

1. Cultural control

a. Sanitation and pruning

Removing infested plant material and maintaining field hygiene can help reduce initial mite populations. Regular pruning of infested branches improves air circulation, discouraging mite buildup and aiding in early detection.

b. Crop rotation

Rotating susceptible crops with non-host crops interrupts the life cycle of soil-borne mite species and reduces the buildup of resistant mite populations.

2. Biological control

a. Predatory mites (e.g., Phytoseiulus persimilis)

Predatory mites such as Phytoseiulus persimilis are highly effective in controlling spider mites. A single predatory mite can consume up to 20 spider mite eggs or 5 adult mites per day. These biocontrol agents are commercially available and are widely used in greenhouses and open fields.

b. Entomopathogenic fungi

Fungi such as Beauveria bassiana and Hirsutellathompsonii infect and kill mite populations under humid conditions. These bioagents are applied as foliar sprays and are compatible with many IPM strategies.

3. Chemical control

a. Acaricides and application timing

Acaricides such as abamectin, spiromesifen, and fenpyroximate are commonly used against mite infestations. These chemicals target specific mite life stages and must be applied at early infestation levels for maximum efficacy. Repeated applications may be required due to rapid reproduction cycles.

b. Resistance management

Mite populations are prone to developing resistance due to their short generation time and frequent exposure to chemicals (Croft *et.al.,* 1988). Rotating acaricides with different modes of action and limiting unnecessary pesticide applications are essential for maintaining long-term control.

4. Integrated Pest Management (IPM) approaches

IPM for mites involves regular field scouting, the use of economic threshold levels, and the integration of biological, cultural, and chemical tools. Monitoring tools such as sticky traps, visual inspections, and leaf sampling help detect early infestations. When population thresholds are reached, targeted interventions such as release of predatory mites, application of biopesticides, or selective acaricides are used to suppress pest populations while preserving beneficial organisms. Sustainable mite management depends on early detection, accurate identification, and a well-timed combination of control tactics.

Snails and Slugs

A. Classification and Identification

1. Phylum: Mollusca; Class: Gastropoda

Snails and slugs belong to the phylum Mollusca and are classified under the class Gastropoda. This class includes soft-bodied, unsegmented animals that typically have a muscular foot and a head with sensory tentacles. Among gastropods, snails are characterized by the presence of an external spiral shell, while slugs lack a prominent shell or possess only a vestigial one. Gastropods are one of the most diverse classes of molluscs, with several species known to be phytophagous, feeding on living plant tissues and causing significant agricultural losses.

2. Snails vs. slugs: anatomical and ecological differences

Snails have a hard, coiled, calcium-based shell into which they retract for protection against predators and desiccation. Slugs, on the other hand, either completely lack a shell or have a reduced internal shell. This anatomical difference makes slugs more prone to water loss, leading to their increased activity during nighttime or periods of high humidity. Ecologically, both snails and slugs are soil dwellers and are most active in moist environments such as irrigated fields, greenhouses, and nurseries. Their feeding behavior and preferred microhabitats overlap, though slugs tend to be more concealed and difficult to detect.

B. Morphological Characteristics

1. Shell presence (snails) vs. absence (slugs)

The primary morphological distinction between snails and slugs is the shell. Snails carry a visible coiled shell that offers them mechanical protection and serves as a water reservoir. This adaptation allows them to survive dry conditions by sealing the shell with a mucous membrane. Slugs, having no such shell, depend heavily on external moisture for their survival and typically remain hidden in soil crevices, leaf litter, and under stones during dry conditions.

2. Tentacles and mucous secretion

Both snails and slugs possess two pairs of tentacles on their heads. The upper pair, longer and equipped with eyes at the tips, serves as visual organs, while the lower pair functions in tactile and chemical sensing. Their bodies are covered in mucous glands that produce a slimy secretion aiding in locomotion, moisture retention, and protection from abrasive surfaces. This mucous trail is also a distinctive diagnostic feature during field scouting for gastropod infestations.

C. Biology and Life Cycle

1. Egg laying, hatching, and maturation

Snails and slugs are hermaphroditic, meaning each individual possesses both male and female reproductive organs, although they usually mate with others for reproduction. After copulation, they lay clusters of spherical, gelatinous eggs in moist soil, under debris, or in cracks near host plants. Depending on the species and environmental conditions, eggs hatch in 1 to 3 weeks. Juveniles resemble adults but are smaller in size and take 3 to 6 months to reach maturity. A single adult can lay over 400 eggs in a season, enabling populations to expand rapidly under favorable conditions.

2. Moisture-dependent behavior and seasonal activity

The activity of snails and slugs is closely tied to environmental moisture. They are typically nocturnal and most active during and after rainfall or irrigation events. During dry or hot periods, they enter a state of dormancy called estivation by retracting into soil or hidden locations. Their population density increases significantly during the monsoon and post-monsoon periods, leading to major outbreaks in sensitive crops. High humidity levels above 75% and moderate temperatures between 18°C and 25°C are ideal for their development and feeding activity.

D. Symptoms of Infestation

1. Irregular holes in leaves and stems

Feeding damage caused by snails and slugs is easily identifiable due to the irregular, ragged holes they leave on leaves, flowers, and soft stems. They chew on the plant surface using a rasping tongue-like structure called a radula. Damage is especially severe in seedlings, leafy vegetables, and low-lying crops where the entire shoot may be consumed.

2. Mucous trails

A slimy, shiny mucous trail on soil, plant surfaces, or containers is a key indicator of gastropod presence. This secretion dries to form silvery lines, which are used in field scouting to detect activity during early morning hours or after irrigation.

3. Damage to seedlings and low-lying crops

Gastropods prefer succulent plant tissues and are particularly damaging to newly transplanted seedlings, lettuce, cabbage, spinach, and other leafy crops. They often feed at the base of stems or at soil level, leading to stem girdling, plant collapse, and significant stand losses. In nursery beds, even a few individuals can destroy dozens of seedlings overnight.

E. Common Agricultural Species

1. Giant African snail (Achatina fulica)

Achatina fulica is among the most destructive terrestrial molluscs and is listed as one of the world's 100 worst invasive species. It can grow up to 20 cm in length and feeds on over 500 species of plants, including banana, papaya, coffee, and various vegetables. It breeds prolifically and lays up to 1000 eggs annually. Its presence poses serious threats not only due to feeding damage but also as a carrier of parasitic nematodes harmful to humans.

2. Garden slug (Derocerasreticulatum)

Derocerasreticulatum, commonly known as the grey field slug or garden slug, is a major pest of vegetables and ornamental crops. It thrives in damp, shaded environments and is particularly destructive in lettuce, brassicas, strawberries, and potatoes. It burrows into tubers and fruits, reducing marketability. The species can produce multiple generations in a year and is capable of reproducing rapidly under high humidity.

F. Economic Importance and Crop Losses

1. Damage to horticultural crops

Snails and slugs cause direct feeding damage and reduce the quality and marketability of horticultural produce (Barua *et.al.,* 2021). In leafy vegetables like spinach and lettuce, infestations can render the entire crop unsellable. Fruit crops such as strawberries and papaya suffer from surface feeding and burrowing. Studies have shown that gastropod pests can reduce marketable yields by 20% to 40% during peak infestation periods.

2. Problems in nurseries and vegetable farms

Seedlings in nurseries are particularly vulnerable due to their tender tissues and close spacing. Slugs and snails often go unnoticed until the damage becomes visible, by which point a significant proportion of seedlings may be lost. Vegetable farms using plastic mulch and drip irrigation create favorable microhabitats that retain moisture, further promoting slug and snail activity. Reports from multiple horticultural regions have documented daily losses of up to 30% of seedling stock in uncontrolled outbreaks.

G. Management Strategies

1. Cultural control

a. Hand picking and destruction

Manual collection of snails and slugs during early morning or late evening hours is an effective control method in small-scale fields and nurseries. Regular removal prevents population buildup and reduces egg-laying sites.

b. Removal of moist habitats

Gastropods rely on moist microhabitats for shelter. Removing weeds, leaf litter, stones, and other debris from the field edges and nursery areas reduces their hiding places and exposes them to predators and environmental stress.

c. Use of barriers (e.g., copper tape)

Copper-based barriers placed around seedbeds and containers act as repellents due to the reaction between the mollusc's mucous and metal ions, which generates a mild electric shock. This method is particularly effective in greenhouses and small-scale protected cultivation.

2. Biological control

a. Natural predators (e.g., birds, beetles)

Birds such as ducks and ground-feeding species, as well as carabid beetles and certain frogs, prey on gastropods and can help reduce their numbers. Encouraging biodiversity around fields and minimizing the use of broad-spectrum insecticides supports these natural enemies.

b. Use of parasitic nematodes

Nematodes such as Phasmarhabditis hermaphrodita specifically target slugs by invading their body cavity and releasing symbiotic bacteria that kill the host. Commercial formulations of these nematodes are available and are effective in moist conditions with minimal risk to non-target organisms.

3. Chemical control

a. Molluscicides (e.g., metaldehyde, iron phosphate)

Chemical baits containing metaldehyde or iron phosphate are commonly used to control slugs and snails. These act as attractants and toxins, causing dehydration or internal disruption. Iron phosphate is preferred in organic farming systems due to its low toxicity to pets and humans.

b. Application methods and precautions

Molluscicides should be applied in the evening or after irrigation when gastropods are most active. Pelleted formulations should be evenly distributed around plant bases and not directly on edible parts. Over-application should be avoided to prevent environmental contamination.

4. IPM Techniques

a. Monitoring and threshold levels

Regular monitoring of slug and snail activity through bait traps and mucous trail identification helps determine the timing of control measures. Threshold levels vary depending on the crop and growth stage but early intervention is critical to prevent economic losses.

b. Use of traps and baits

Beer traps, bran bait, and other attractant-based traps are effective for capturing and reducing gastropod populations. These methods are environmentally friendly and can be integrated with other IPM components for long-term suppression. Gastropod pest management requires a combination of cultural, biological, and chemical measures customized to local environmental conditions and cropping systems. Early detection and timely intervention are key to minimizing damage and preserving crop yield and quality.

Comparation of Mites vs. Molluscan Pests

A. Differences in morphology, biology, and habitat

Mites and molluscan pests such as snails and slugs differ fundamentally in their morphology, biological processes, and ecological niches (Sallam *et.al.,* 2012). Mites are microscopic arthropods belonging to the class Arachnida and have segmented bodies with four pairs of legs in their nymph and adult stages. Their body is typically soft and oval-shaped, with mouthparts adapted for piercing and sucking plant cell contents. They lack wings and antennae and are highly adapted for feeding on plant tissues, especially under dry and warm conditions. Molluscan pests, which include snails and slugs, are non-arthropod invertebrates from the phylum Mollusca and class Gastropoda. Snails possess a distinct external spiral shell, while slugs have either no shell or a vestigial internal one. These pests have a broad, muscular foot for movement and use a radula a toothed tongue-like structure for scraping and chewing plant material. Molluscs are larger, easily visible, and thrive in moist environments, particularly during monsoon seasons or in irrigated fields. Their activity is highly moisture-dependent, and they remain inactive during dry periods by hiding in cool, damp habitats or entering dormancy.

B. Damage patterns and symptoms

Mites feed on plant sap by puncturing epidermal cells, leading to physiological damage without immediately visible tissue removal. This mode of feeding results in stippling, leaf discoloration, chlorosis, bronzing, and in severe cases, leaf drop and necrosis. Webbing is a characteristic symptom of spider mite infestation, while certain tarsonemid and eriophyid mites cause curling, twisting, and deformation of young tissues and fruits. Mite infestations often go unnoticed until significant physiological stress becomes evident due to their minute size and hidden feeding sites on the undersides of leaves. Molluscan pests, by contrast, cause physical destruction of plant tissues. They create irregular, large holes in leaves, flowers, and fruit surfaces by rasping away plant matter. Damage is easily visible and often occurs overnight, especially in young seedlings and low-lying crops. Mucous trails left behind on foliage and soil are key diagnostic features. In crops such as lettuce, spinach, and strawberries, molluscan feeding can render the entire harvest unmarketable due to contamination and tissue loss. To mites, which usually damage the physiological functions of plants, snails and slugs directly consume biomass, often leading to plant death or yield loss.

C. Control challenges and strategies

Management of mites presents specific challenges due to their rapid reproductive rates, minute size, and ability to develop resistance to acaricides. Effective chemical control requires precise application timing, rotation of active ingredients to avoid resistance, and thorough coverage of leaf undersides. Biological control using predatory mites such as Phytoseiulus persimilis and fungal pathogens like Beauveria bassiana has proven effective under controlled conditions. Monitoring with magnifying lenses and routine scouting is essential, as mite populations can explode rapidly in dry, hot conditions without obvious early symptoms. Molluscan pests pose different management challenges. Their activity is intermittent and heavily influenced by moisture and temperature, making monitoring and control timing unpredictable. Manual collection is labor-intensive but effective for small areas. Chemical control using molluscicides such as metaldehyde and iron phosphate provides effective results, especially when baited formulations are applied during high humidity periods. Molluscs are more visible and can be controlled using traps, barriers, and habitat modifications like debris removal and field drainage. Biological control options such as predatory beetles and parasitic nematodes (*Phasmarhabditis hermaphrodita*) have shown success in reducing populations but require high soil moisture to be effective. Integrated Pest Management strategies differ between the two groups. Mite management emphasizes early detection, biocontrol integration, and acaricide rotation, while molluscan pest management focuses on habitat management, bait-based control, and moisture regulation. Despite these differences, both groups require regular monitoring and timely interventions to prevent economic losses.

D. Case studies of outbreaks and control success stories

A major outbreak of *Tetranychus urticae* in protected tomato cultivation resulted in over 40% yield loss due to the rapid buildup of mite populations under warm and dry conditions. Control was achieved by introducing predatory mites at a ratio of 1:10 (predator to pest) and rotating miticides such as spiromesifen and abamectin. Economic thresholds were applied based on leaf damage and mite density, allowing for targeted intervention that reduced input costs and pesticide usage. In a separate event, an outbreak of Achatina fulica in banana plantations led to severe defoliation and fruit damage. The population was reduced through a combination of cultural methods, including removal of sheltering debris, manual collection during early morning hours, and the application of metaldehyde-based baits during peak activity periods. Use of perimeter copper tape around nurseries prevented reinvasion. Within three weeks, visible damage decreased by over 60%, and subsequent monitoring indicated a significant drop in population density. These examples illustrate that although mites and molluscan pests require distinct management approaches due to differences in biology and behavior, both can be effectively controlled through integrated, timely, and environment-specific strategies. Successful management depends on early detection, knowledge of pest ecology, and the careful combination of cultural, biological, and chemical methods tailored to the pest and crop system.

Impact on Crop Health and Yield

A. Reduction in photosynthesis and growth

Infestations caused by non-insect pests such as mites, snails, and slugs result in direct and indirect damage to crops, beginning with a measurable decline in photosynthetic efficiency (Elango *et.al.,* 2022). Mites, particularly species like *Tetranychus urticae*, feed by puncturing epidermal cells and extracting chlorophyll-containing cell contents. This feeding leads to stippling, bronzing, and chlorosis of leaves, which significantly reduces the surface area available for photosynthesis. The physiological stress on plants during active growth periods reduces energy capture and carbohydrate synthesis, directly impacting vegetative growth and flowering. In crops such as brinjal and cotton, spider mite infestations can lower net photosynthetic rates by over 50%, leading to poor plant vigor and delayed development. Molluscan pests like slugs and snails remove portions of the leaf lamina entirely through their rasping feeding mechanism. The physical loss of foliage in seedlings and leafy crops such as lettuce, spinach, and mustard leaves the plants with insufficient leaf area to sustain growth, resulting in stunting and poor stand establishment.

B. Secondary infections due to pest injury

Feeding wounds caused by non-insect pests create ideal entry points for secondary pathogens, compounding crop damage. Mites often leave microscopic punctures and necrotic patches on plant surfaces that become colonized by bacterial and fungal pathogens. This is particularly evident in fruit crops like citrus and grapes, where rust mites and bud mites contribute to fruit blemishes that are later infected by sooty mold or Botrytis species. In cereals and pulses, feeding damage by eriophyid mites facilitates the entry of smut and rust fungi. Molluscan pests contribute to secondary infections by introducing soil-borne pathogens through mucous-contaminated feeding areas. Slugs feeding on lettuce and cabbage often introduce Pseudomonas and Erwinia bacteria, which cause soft rot and foul odor. Their mucous trails also harbor fungal spores and nematodes, leading to complex disease-pest interactions that are difficult to control once established. These compounded effects increase the need for additional pesticide applications, raising production costs and environmental risk.

C. Yield and quality losses in major crops

Quantitative and qualitative yield losses due to mites and molluscs vary across crops and seasons but are often economically significant. In tea plantations, red spider mites reduce photosynthetic area and cause up to 25% reduction in leaf harvest weight, lowering the volume and quality of processed tea. In cotton, mite infestations result in poor boll development and leaf senescence, with yield losses reaching 30% under severe outbreaks. Vegetable crops such as tomato, chili, and brinjal experience both direct yield reduction and downgrading of produce quality due to fruit blemishes and leaf loss. Molluscan pests like Achatina fulica have been recorded to cause 40–60% loss in banana and papaya yields in affected regions by feeding on the fruits and reducing marketable quantity. Leafy vegetables like spinach and lettuce are particularly vulnerable to molluscan damage, with entire batches rendered unfit for sale due to contamination by mucous or feeding scars. Quality degradation is not limited to physical appearance but also affects storage life, shelf stability, and transportability, thereby influencing market acceptance and pricing.

D. Cost of management and losses in market value

The economic burden of controlling non-insect pests and mitigating their effects on crop quality is substantial. Farmers are required to invest in frequent monitoring, multiple rounds of pesticide or molluscicide applications, and manual removal or habitat modification strategies. The cost of managing spider mites in high-value crops such as capsicum under polyhouse conditions can exceed ₹10,000 per hectare due to the need for biological control agents and acaricides. Mollusc management using baits, traps, and labor-intensive collection methods also incurs high operational costs, particularly during the rainy season. Market value losses occur not only from quantity reduction but also from grade downgrading. For example, citrus fruits affected by rust mites may be sold at 30–40% lower prices due to scarring, even if internal quality is unaffected. In export-oriented crops like grapes and mangoes, visual blemishes caused by mite feeding or slug damage can lead to rejection of consignments and breach of phytosanitary regulations. These combined losses direct yield reduction, increased input costs, and decreased market value underscore the significance of non-insect pests as serious threats to agricultural profitability and sustainability.

Recent Advances in Non-Insect Pest Management

A. Molecular tools in pest identification

Advancements in molecular biology have significantly enhanced the identification and classification of non-insect pests, especially those with cryptic morphology or minute size, such as mites. Traditional methods relying on microscopic features are often time-consuming and require high expertise. DNA barcoding using mitochondrial cytochrome oxidase I (COI) gene sequences has become a reliable tool for distinguishing closely related mite species, such as those within the Tetranychusgenus. This technology helps in rapid and accurate species-level identification, which is crucial for implementing specific management strategies. Quantitative PCR (qPCR) and loop-mediated isothermal amplification (LAMP) are also being applied for field-level diagnostics. These tools are particularly useful for early detection of invasive or resistant populations and support surveillance systems aiming to prevent outbreaks. Molecular diagnostics enable the development of geo-specific pest databases and contribute to designing region-appropriate control programs based on species prevalence and population genetics.

B. Innovations in biocontrol agents

Biological control is undergoing a transformation through innovations in formulation, delivery, and agent selection. Predatory mites such as Neoseiulus californicus and Phytoseiulus persimilis are now being mass-reared using artificial diets, which reduces production costs and improves field application consistency. Advances in microbial biocontrol include improved strains of entomopathogenic fungi like Beauveria bassiana and Metarhizium anisopliae, which have shown high virulence against various mite species under controlled humidity and temperature conditions. New formulations with extended shelf life and UV resistance allow for better field performance. For molluscan pests, research has led to the development of nematode-based bio-pesticides using Phasmarhabditis hermaphrodita, which infects and kills slugs without harming non-target organisms. Encapsulation technology and gel-based delivery systems are being explored to enhance nematode survival and infectivity. The integration of multiple biocontrol agents, including natural predators like ground beetles and microbial formulations, is increasingly being adopted in IPM frameworks, reducing reliance on synthetic chemicals and promoting ecological balance.

C. Role of precision agriculture in monitoring non-insect pests

Precision agriculture is revolutionizing pest monitoring through the use of sensor-based systems, remote sensing, and data analytics (Aziz *et.al.,* 2025). For mites, thermal imaging and multispectral cameras mounted on drones or stationary platforms detect early signs of infestation based on leaf temperature changes and reflectance indices. Real-time data from these tools can identify hotspots of pest activity, allowing targeted intervention and reducing blanket pesticide applications. Automated weather stations integrated with pest forecasting models are being used to predict outbreaks based on humidity, temperature, and leaf wetness parameters known to influence mite and mollusc behavior. For molluscs, smart traps equipped with sensors and cameras record activity levels, helping in determining the optimal time for bait application. Geographic Information Systems (GIS) support the mapping of pest spread patterns across landscapes, enabling strategic planning of control operations. Mobile applications and cloud platforms are now being employed for farmer-level data entry, image sharing, and access to expert recommendations. These digital tools increase the efficiency, accuracy, and timeliness of non-insect pest management practices.

D. Policy and quarantine measures for invasive molluscs

The spread of invasive molluscan species such as Achatina fulica and Theba pisana has raised serious concerns due to their destructive feeding habits and role as vectors of plant and human pathogens. Quarantine protocols have been strengthened to prevent the unintentional introduction of these pests through international trade, nursery stock, and agricultural commodities. Regulatory authorities enforce mandatory inspection and certification for plant material transported across borders. Heat treatment, salt dipping, and physical inspection are being applied to nursery stock and shipping containers. Invasive species risk assessments are now a standard part of phytosanitary regulations, and early detection systems are being implemented at ports and border checkpoints. Public awareness campaigns and farmer training programs are conducted to enhance surveillance and reporting of new incursions. Surveillance programs often include pheromone or attractant-based traps, which are deployed in high-risk zones for early detection. Legislative support and enforcement mechanisms play a critical role in eradicating localized populations before they spread. These efforts are aligned with international guidelines set by organizations such as the International Plant Protection Convention (IPPC) to ensure coordinated action against invasive non-insect pests across agro-ecological zones.

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Chapter 11

Concept and Application of Integrated Pest Management (IPM)

Sanjeev Kumar*[1], Surekha Kamlesh Kurankar[2] and Priya Kashyap[3]

[1]*Assistant professor, School of agriculture science, K.K university, Biharsharif, Nalanda.*

[2]*Assistant Professor, Department of Zoology, R C PATEL Arts Commerce and Science College Shirpur*

[3]*Zoology, Entomology, CCSU, Meerut College Meerut*

The management of pests in agricultural systems dates back thousands of years, with early civilizations using manual methods, ash, plant extracts, and fire to protect crops. Ancient records from Mesopotamia, Egypt, and China mention the use of natural materials to deter insects and rodents. Traditional farming practices often relied on physical barriers, cultural rotations, and locally sourced botanical deterrents. As agriculture expanded and specialized, pest outbreaks became more frequent and destructive. With the advent of chemical pesticides in the late 19th and early 20th centuries, pest control saw a shift towards synthetic solutions. The discovery of DDT during World War II marked a turning point, offering highly effective control of major pest species. This led to the widespread adoption of broad-spectrum insecticides, revolutionizing agriculture but also introducing environmental and health concerns. Over time, the indiscriminate use of pesticides resulted in unintended consequences such as resistance development, destruction of natural enemies, secondary pest outbreaks, and pesticide residues in food and water.

A. Emergence of Integrated Pest Management (IPM)

Integrated Pest Management (IPM) emerged during the mid-20th century as a response to the ecological imbalances caused by overreliance on chemical control (Abrol *et.al.,* 2012). The term was formally introduced in the 1960s, following scientific evaluations that highlighted the importance of ecosystem-based strategies. Researchers emphasized the need to combine various control methods biological, cultural, mechanical, and chemical in a way that minimizes risks to humans, non-target organisms, and the environment. IPM was built on the principle that pests should be managed, not eradicated, and that control actions should only be taken when economic thresholds are exceeded. Academic institutions, international organizations, and agricultural development agencies began promoting IPM as a sustainable alternative, supported by real-time monitoring, economic analysis, and ecological knowledge. By the 1980s and 1990s, IPM became an official policy goal in several national agricultural systems, with demonstration projects and field schools helping to disseminate best practices.

B. Rationale for adopting IPM in modern agriculture

Modern agriculture faces a range of complex challenges, including pest resistance, biodiversity loss, climate variability, rising input costs, and consumer concerns about pesticide residues. Under these conditions, IPM offers a science-based, holistic framework that enhances productivity while safeguarding ecological integrity. The rationale for IPM adoption is rooted in its adaptability and cost-effectiveness. It allows farmers to reduce input costs by minimizing unnecessary pesticide applications and improving long-term crop health through ecological balance. IPM also plays a key role in meeting food safety standards for domestic and export markets, as many importing countries impose strict limits on chemical residues. In resource-limited settings, IPM provides low-cost options such as natural predators and trap cropping, reducing dependence on commercial agrochemicals. Studies have shown that farms practicing IPM can reduce pesticide use by 30–50% while maintaining or increasing crop yields. These results highlight the method's potential to contribute to both economic stability and sustainable resource use in agriculture.

C. Global and national relevance of IPM practices

Integrated Pest Management has gained wide recognition at both international and national levels as a cornerstone of sustainable agriculture. Global organizations such as the Food and Agriculture Organization (FAO), World Bank, and UNEP endorse IPM through funding, policy advocacy, and training programs. IPM is also embedded in climate-resilient agriculture frameworks and biodiversity conservation strategies. Countries across Asia, Africa, Europe, and Latin America have adopted IPM as part of their agricultural development agendas. Farmer field schools, participatory extension models, and mobile-based advisory platforms have been deployed to promote awareness and implementation. The relevance of IPM is not limited to large-scale farms; it is equally applicable to smallholders and subsistence producers who require affordable and locally adapted pest control methods. With the increasing integration of digital tools, precision agriculture, and data-driven decision-making, IPM is evolving into a dynamic approach capable of addressing the demands of both environmental sustainability and global food security.

Definition and Objectives of IPM

A. Scientific definition of IPM

Integrated Pest Management (IPM) is defined as a science-based, decision-making system used to manage pests by combining multiple strategies that are economically viable, environmentally sound, and socially acceptable. The Food and Agriculture

Organization (FAO) describes IPM as the careful consideration of all available pest control techniques and the subsequent integration of appropriate measures that discourage the development of pest populations while minimizing risks to human health, beneficial organisms, and the environment. This approach relies on regular monitoring, threshold-based action, and the use of biological, cultural, physical, and chemical tools in a compatible and coordinated manner. Unlike reactive pest control models, IPM is preventive and adaptive, aiming to maintain pest levels below economic injury thresholds rather than pursuing eradication.

B. Key goals and guiding principles

The primary goal of IPM is to maintain pest populations at levels that do not cause economic harm while preserving the ecological balance of the agro-ecosystem. IPM promotes rational pest control decisions based on continuous monitoring, pest biology, and crop vulnerability. One guiding principle is the establishment of economic threshold levels (ETLs), which define the pest density at which control actions must be taken to prevent unacceptable crop damage. Another key principle is the conservation of natural enemies, such as predators, parasitoids, and microbial antagonists, which play a crucial role in suppressing pest outbreaks. IPM also emphasizes the importance of selecting pest management strategies that minimize environmental contamination, reduce human exposure to toxic substances, and delay the development of pest resistance to control measures. Through integration and timing of compatible tactics, IPM ensures that crop protection is both sustainable and scientifically informed.

C. Need for sustainable pest management strategies

Agricultural ecosystems are facing increasing pressure due to climate change, soil degradation, pesticide resistance, and food safety concerns (Iqbal *et.al.,* 2025). The heavy reliance on chemical pesticides has led to serious problems, including contamination of water bodies, destruction of beneficial organisms, resurgence of secondary pests, and persistent residues in harvested produce. Pest resistance has become a major challenge, with over 600 insect and mite species now documented as resistant to at least one class of pesticides. This scenario creates an urgent demand for alternative and sustainable pest control strategies that are effective over the long term. IPM offers a solution that aligns with ecological sustainability by promoting biodiversity, reducing input costs, and enabling resilience against pest outbreaks. By integrating traditional knowledge with modern scientific advancements, IPM can be tailored to various agro-climatic zones and cropping systems, ensuring more stable yields and better environmental health.

D. Comparison with conventional pest control approaches

Conventional pest control is typically characterized by calendar-based pesticide applications with little regard for pest population levels or the presence of natural enemies. This approach often leads to overuse of chemicals, development of resistance, and unintended harm to non-target species. IPM relies on informed decision-making, where actions are only taken when pest populations reach critical thresholds. While conventional methods may offer rapid knockdown effects, they often create long-term vulnerabilities in agroecosystems. IPM emphasizes ecosystem services, such as biological control and habitat management, which contribute to natural pest suppression. Economically, IPM has shown to reduce pesticide use by 30–50% without compromising yields, as observed in crops such as cotton, rice, and vegetables. This makes IPM not only more environmentally responsible but also more cost-effective over time. By promoting minimal reliance on pesticides and maximizing the use of ecological processes, IPM represents a shift from input-intensive to knowledge-intensive crop protection.

Principles of IPM

A. Prevention rather than cure

A fundamental principle of Integrated Pest Management (IPM) is the emphasis on preventive measures to reduce the likelihood of pest outbreaks before they occur. This proactive approach involves designing crop ecosystems that are less conducive to pest development through proper planning, cultural practices, and habitat management. Techniques such as crop rotation, use of pest-resistant varieties, timely planting and harvesting, sanitation, and destruction of crop residues help in limiting pest establishment and reproduction. By avoiding conditions that favor pest proliferation, farmers can reduce dependency on reactive interventions like chemical pesticides. Preventive practices also minimize disruption to beneficial organisms, making the crop environment more stable and resilient over time. Preventive strategies are particularly important in long-duration and high-value crops, where pest incursions can cause significant economic losses if not addressed early.

B. Pest threshold and economic injury level

Integrated Pest Management is guided by the principle that not all pests require immediate control. Intervention is based on pest population levels relative to the economic threshold level (ETL), which is the pest density at which action must be taken to prevent economic damage. The concept of the Economic Injury Level (EIL) defines the lowest pest population that will cause economic harm greater than the cost of control. The ETL is usually set slightly below the EIL to provide a margin of safety. This principle ensures that control measures are economically justified and not applied unnecessarily. For example, in cotton, the ETL for bollworm may be defined as five larvae per 10 plants, beyond which significant yield loss can occur. Ignoring thresholds can lead to overuse of pesticides and secondary pest outbreaks, while respecting them ensures resource-efficient management and preservation of natural enemies.

C. Monitoring and pest surveillance

Accurate monitoring and regular pest surveillance form the backbone of decision-making in IPM. Monitoring involves systematic observation and sampling of pest populations, crop conditions, and natural enemies over time. Techniques include visual inspection, sweep netting, pheromone trapping, light trapping, and sticky cards, depending on the pest and crop. Surveillance data provide critical information on pest dynamics, enabling timely intervention and reducing unnecessary pesticide applications. Consistent scouting allows for the early detection of pest activity before it reaches damaging levels. Modern tools such as remote sensing, GPS-enabled devices, and mobile-based apps are also being integrated into surveillance programs for real-time tracking and forecasting. Effective surveillance not only helps in the timely implementation of control measures but also supports resistance management and long-term planning by identifying pest trends and hotspot areas.

D. Ecological balance and natural enemy conservation

Preserving the ecological balance of the cropping system is a central tenet of IPM. Healthy agroecosystems support a wide array of beneficial organisms, including predators, parasitoids, and entomopathogenic fungi, which play a natural role in suppressing pest populations. The use of broad-spectrum insecticides can disrupt this balance by eliminating non-target species and leading to pest resurgence. IPM encourages habitat management practices that conserve natural enemies, such as maintaining vegetation strips, planting nectar-producing border crops, and reducing unnecessary pesticide use. Conservation biological control is a cost-effective and sustainable method that requires no external input, relying instead on the ecosystem's inherent capacity to regulate pests. Field studies have demonstrated that farms with higher predator diversity experience fewer pest outbreaks and require less chemical intervention. This ecological principle enhances long-term pest control while promoting biodiversity and environmental health.

E. Decision-making based on data

IPM relies on informed decision-making grounded in empirical data rather than routine schedules or assumptions. Data collected from monitoring, field records, pest thresholds, weather patterns, and previous pest occurrences form the basis for selecting and timing control interventions. Decision-support systems (DSS), modeling tools, and forecasting algorithms help predict pest emergence and suggest appropriate management tactics. These tools allow for precise applications of control measures only when needed, improving cost-efficiency and reducing ecological disruption. For example, models predicting aphid outbreaks in cereal crops use temperature and humidity data to estimate migration periods, enabling timely deployment of traps or natural enemies. Data-driven decision-making ensures transparency, accountability, and adaptability in pest management, aligning with the broader goals of precision agriculture and sustainable farming practices. Through careful analysis and evidence-based strategies, IPM enhances both crop protection and economic viability.

Components of IPM

A. Cultural Control

Cultural practices form the first line of defense in Integrated Pest Management by modifying the farming environment to make it less favorable for pest establishment and reproduction. These methods are often cost-effective and environmentally safe, involving the manipulation of agronomic techniques that directly impact pest behavior and population dynamics.

1. Crop rotation

Crop rotation is an important strategy that interrupts pest life cycles by changing the host crop (Aslam *et.al.,* 2024). Continuous cultivation of a single crop can lead to the buildup of host-specific pests and pathogens in the soil. Rotating crops such as maize with legumes or oilseeds helps reduce the presence of pests like stem borers and nematodes. Studies have shown that crop rotation can lower pest infestation levels by 40–60% in cereal-based systems.

2. Intercropping and trap cropping

Intercropping and trap cropping utilize spatial diversity to deter pest colonization. Intercropping maize with cowpea or sorghum with pigeon pea can reduce pest loads by providing physical barriers and promoting the activity of beneficial insects. Trap crops like marigold in tomato fields attract pests such as *Helicoverpa armigera*, diverting them from the main crop and allowing for targeted control. These systems enhance pest management while improving soil health and overall yield.

3. Timely sowing and harvesting

Timely sowing and harvesting are essential for avoiding peak pest activity periods. Synchronizing planting schedules with pest-free windows can significantly reduce early pest pressure. For example, early sowing of mustard can avoid severe aphid infestations, while timely harvesting of rice limits the chances of late-season stem borer attacks.

4. Use of resistant varieties

Use of resistant varieties is a genetic approach to pest management, relying on cultivars bred for tolerance or resistance to specific pests. High-yielding varieties of cotton, rice, and wheat have been developed with resistance to bollworms, brown planthoppers, and leaf rust. Incorporating such varieties reduces the need for external pest control and supports sustainable production.

B. Mechanical and Physical Control

Mechanical and physical measures involve the use of manual tools, devices, and environmental manipulation to remove, kill, or exclude pests. These methods are especially useful in smallholder and organic farming systems.

1. Hand picking and destruction

Hand picking and destruction of visible pests like caterpillars, egg masses, and infested plant parts is widely practiced in vegetable and fruit crops. This method helps prevent pest outbreaks at an early stage when populations are low. Although labor-intensive, it can reduce pest load by up to 70% in crops like tomato and okra.

2. Light traps, sticky traps, pheromone traps

Light traps, sticky traps, and pheromone traps are widely used for monitoring and managing pest populations. Light traps attract nocturnal insects such as moths, while sticky traps are effective for whiteflies and aphids. Pheromone traps use species-specific chemical signals to attract and trap male insects, disrupting mating cycles. Mass trapping using pheromones has significantly reduced the incidence of Spodoptera in maize fields.

3. Use of barriers and temperature control

Use of barriers and temperature control includes physical structures such as nets, row covers, and trenches to prevent pest entry or movement. Temperature manipulation, such as solarization of soil or heat treatment of stored grains, effectively kills insect eggs and larvae. Cold storage is also employed to suppress the development of storage pests like *Sitophilus oryzae*.

C. Biological Control

Biological control uses natural enemies of pests to reduce their populations, providing an eco-friendly and sustainable method within IPM systems.

1. Role of predators, parasitoids, and pathogens

Role of predators, parasitoids, and pathogens is critical in regulating pest populations. Predatory insects like ladybird beetles feed on aphids, while parasitoids such as Trichogramma wasps lay their eggs inside pest eggs, preventing them from hatching. Entomopathogenic fungi like Beauveria bassiana infect and kill a range of soft-bodied insects, adding a microbial dimension to pest control.

2. Use of bioagents (e.g., Trichogramma, Beauveria, NPV)

Use of bioagents such as *Trichogramma chilonis*, Beauveria bassiana, and nuclear polyhedrosis viruses (NPVs) has been successfully demonstrated in crops like sugarcane, cotton, and cabbage. Field applications of Trichogramma have resulted in a 50–70% reduction in egg-laying by Helicoverpa moths. NPVs have been used effectively to control *Spodoptera litura* in soybean and groundnut.

3. Augmentative and conservation biological control

Augmentative and conservation biological control involves the release of natural enemies in large numbers and modifying the environment to conserve existing beneficial species. Planting flowering strips, avoiding broad-spectrum insecticides, and maintaining habitat diversity help sustain predator and parasitoid populations across cropping seasons.

D. Chemical Control

While IPM promotes reduced dependence on chemicals, judicious use of pesticides remains an important component for managing high pest pressure situations.

1. Judicious use of pesticides

Judicious use of pesticides means applying chemicals only when pest populations exceed economic thresholds. This approach minimizes the environmental impact and reduces risks to human health and non-target species. Proper selection of active ingredients and formulations is essential for targeted control.

2. Selective and compatible chemicals

Selective and compatible chemicals are chosen to be effective against target pests while sparing beneficial organisms (Gentz *et.al.,* 2010). Use of insect growth regulators and systemic insecticides with short residual periods supports compatibility with biological control agents. Avoiding repeated use of the same chemical group helps preserve natural enemy populations.

3. Resistance management

Resistance management is addressed by rotating pesticides with different modes of action and integrating them with non-chemical methods. Continuous exposure to a single pesticide can lead to the development of resistant pest strains. Implementing insecticide resistance management (IRM) strategies helps maintain chemical efficacy and prolongs the utility of available products.

4. Safe application techniques and timing

Safe application techniques and timing ensure that pesticides are used effectively and responsibly. Using calibrated sprayers, protective clothing, and appropriate dosage rates minimizes exposure risks. Evening or early morning applications reduce harm to pollinators and beneficial insects. Weather conditions such as wind and rainfall must also be considered to prevent drift and runoff.

E. Legislative and Quarantine Measures

Governmental regulations play a pivotal role in preventing the introduction and spread of harmful pests and in ensuring safe pest control practices.

1. Quarantine regulations and plant protection laws

Quarantine regulations and plant protection laws are established to control the movement of agricultural commodities across regions. These laws mandate inspection, certification, and treatment of plant materials to prevent the introduction of exotic pests. Quarantine stations at ports and borders enforce these measures.

2. Role in preventing exotic pest invasions

Role in preventing exotic pest invasions is particularly critical as global trade increases the risk of pest entry through imported goods. Effective quarantine measures helped prevent the establishment of pests like the Mediterranean fruit fly and Khapra beetle in many regions. These legal frameworks support IPM by excluding dangerous pests before they establish and disrupt local ecosystems.

Practices and Tools in IPM Implementation

A. Pest scouting and regular field monitoring

Scouting and field monitoring form the operational foundation of Integrated Pest Management. These practices involve systematic observation and sampling of pest populations, crop health, and presence of beneficial organisms across different stages of the crop lifecycle. Trained personnel or farmers conduct regular visits to fields using standard sampling techniques such as visual inspection, sweep netting, quadrant sampling, or trap deployment. Scouting provides accurate data on the density, distribution, and stage of development of pests, which is crucial for deciding if control measures are required. For example, weekly monitoring of aphids in wheat can help determine the onset of infestation and inform whether it surpasses the economic threshold. In rice and cotton, yellow sticky traps and light traps are commonly used to monitor pests like whiteflies, moths, and leaf folders. Reliable scouting data reduce unnecessary pesticide use, enhance biological control decisions, and increase the overall precision of interventions.

B. Use of pest forecasting models

Forecasting models play a key role in anticipating pest outbreaks before they cause significant economic loss. These models use climatic variables such as temperature, humidity, rainfall, and wind speed, in combination with historical pest occurrence data, to predict the timing and severity of infestations. Degree-day models, for example, calculate pest development rates based on accumulated heat units, which are especially useful for insects with temperature-dependent life cycles such as stem borers and aphids. Some models integrate satellite data and remote sensing to assess vegetation health and predict hotspots for pest emergence. These tools allow for early warning and pre-emptive planning, reducing the need for reactive chemical control. Forecasting has proven particularly effective in managing migratory pests like locusts and armyworms, as well as fungal diseases that thrive under specific weather patterns. Accurate forecasts support resource allocation, inform policy decisions, and reduce the risk of widespread crop damage.

C. Record keeping and pest mapping

Maintaining detailed field records is essential for long-term pest management. These records include information on planting dates, crop varieties, input applications, weather conditions, pest sightings, control measures taken, and yield outcomes. Consistent documentation allows for year-to-year comparison and helps identify trends in pest behavior, resistance patterns, and seasonality. Pest mapping, which uses geospatial tools such as GPS and GIS, creates visual representations of pest distribution across fields or regions. This helps detect outbreak zones, track movement over time, and implement area-wide management practices. Data collected from pest mapping can also feed into national pest surveillance systems, contributing to coordinated action at the community or district level. When combined with mobile data entry and cloud-based storage, record keeping and mapping become powerful tools for both individual farmers and agricultural extension agencies to evaluate the effectiveness of IPM practices and guide future decisions.

D. Role of decision support systems (DSS)

Decision support systems are software-based tools that help users make informed pest management decisions by integrating multiple data sources and algorithms (Tambour *et.al.,* 2008). These systems combine field-level data with scientific models, pest biology, environmental conditions, and economic thresholds to recommend optimal control actions. DSS platforms often include user-friendly interfaces, real-time alerts, and scenario analysis features. For example, a DSS may suggest the most effective time for applying a biological agent based on pest development stage and forecasted weather. Some advanced systems also integrate remote sensing data and artificial intelligence to improve prediction accuracy. Use of DSS has been linked to reduced pesticide applications, better timing of interventions, and improved crop health outcomes. They are particularly useful in managing complex pests or when multiple pest species coexist in a field. DSS adoption also encourages standardization of IPM practices, enabling consistent implementation across farms and regions.

E. Integration of multiple tactics for synergy

IPM operates on the principle that combining various pest control strategies leads to more effective, sustainable, and resilient outcomes than relying on a single method. This integration includes the simultaneous or sequential use of cultural, biological, mechanical, and chemical tactics. A cotton field might use Trichogramma releases (biological), pheromone traps (mechanical), resistant varieties (genetic), and need-based spraying of selective insecticides (chemical). When combined appropriately, these tactics create a multi-layered defense system that suppresses pest populations while preserving beneficial organisms and reducing environmental impact. Studies have shown that integrated tactics can reduce pesticide use by up to 50% and increase net returns by improving yield quality and reducing pest resurgence. The synergy between practices also contributes to delaying pest resistance and sustaining the long-term efficacy of available control tools. Successful integration requires a deep understanding of pest ecology, timing of interventions, and compatibility among different control measures, making education and training essential components in achieving effective IPM implementation.

Implementation Strategies in IPM

A. Site-specific and crop-specific planning

The success of Integrated Pest Management largely depends on tailoring strategies to the specific needs of the crop and the local agro-ecological conditions. Pest populations and their natural enemies vary significantly with climate, soil type, cropping patterns, and regional biodiversity. Site-specific planning involves analyzing these local variables to select the most suitable combination of IPM components. For example, rice fields in humid areas are more prone to stem borers and sheath blight, requiring the use of resistant varieties, biological agents, and water management. Arid zones growing cotton may focus on managing sucking pests like whiteflies through trap crops, predator conservation, and threshold-based chemical interventions. Crop-specific strategies account for pest biology, host preference, and crop stage susceptibility. Field trials have demonstrated that pest control efficiency improves by over 40% when region-specific IPM modules are followed rather than generalized recommendations. Developing crop-specific IPM packages through research institutions and validating them under local conditions ensures that recommendations are both practical and effective.

B. On-farm demonstrations and farmer field schools

Practical exposure through on-farm demonstrations is essential for building farmer confidence in IPM practices. These demonstrations showcase the effectiveness of integrated strategies under real-world field conditions, allowing farmers to compare treated and untreated plots. Observing visible differences in pest damage, yield, and input costs helps in overcoming skepticism and encourages adoption. Farmer Field

Schools (FFS) are an educational approach that supports participatory learning. These schools guide groups of farmers through the entire crop cycle, teaching them how to monitor pests, apply thresholds, identify natural enemies, and make decisions based on field observations. Studies show that participants of FFS are more likely to adopt IPM practices and reduce pesticide use by 30% or more. These programs emphasize experiential learning, problem-solving, and knowledge sharing, making them highly effective for scaling IPM among small and marginal farmers.

C. Role of extension services and NGOs

Agricultural extension services act as a critical link between research institutions and the farming community. Extension agents translate scientific knowledge into actionable field-level practices and provide technical support through training sessions, field visits, and printed guides. These services play a vital role in disseminating IPM modules, organizing awareness campaigns, and distributing bio-control products and pheromone traps. NGOs also contribute by implementing community-based pest management projects, training rural youth, and supporting infrastructure for biological control agent production. Collaborative programs led by extension agencies and NGOs have reported significant reductions in pesticide dependency and improvements in crop health. Such efforts not only help in pest management but also empower farmers to make informed decisions and adopt a more ecological approach to crop production.

D. Involvement of stakeholders: farmers, scientists, policymakers

IPM implementation requires coordinated action from multiple stakeholders, each playing a unique role in shaping outcomes. Farmers are central to IPM, as they execute the strategies and observe field-level effects. Scientists contribute by developing pest-resistant varieties, improving biological control techniques, and refining threshold values and forecasting models. Policymakers influence adoption through regulatory frameworks, subsidies, training programs, and certification standards. When these groups work together, the result is a more adaptive and responsive pest management system. Multi-stakeholder platforms and participatory research trials create opportunities for feedback, innovation, and refinement of strategies. Integration of farmer knowledge with scientific insights leads to more realistic and context-specific solutions. Engagement at the policy level can drive support for research funding, infrastructure development, and regulation of pesticide use, aligning national goals with field-level implementation.

E. Use of ICT and mobile applications in IPM

Information and Communication Technologies (ICTs) have emerged as powerful tools for supporting IPM implementation across different scales. Mobile applications, SMS alerts, and interactive voice response systems enable real-time dissemination of pest advisories, weather forecasts, and best practices. Mobile-based pest surveillance platforms allow farmers to report outbreaks and receive tailored advice based on crop stage and local conditions. Satellite data and remote sensing integrated with mobile tools help in early detection of pest hotspots, improving response time and efficiency. Some platforms also include decision-support features that guide pesticide selection based on pest type, crop, and residue safety. Digital tools improve access to knowledge, especially in remote areas with limited access to extension services. Their scalability, low cost, and ease of use make them highly suitable for modernizing IPM implementation and enhancing farmer participation. Field studies have shown that farmers using mobile advisory tools reduce pesticide use by 20–40% and experience more timely pest interventions compared to those relying solely on traditional methods.

Scope and Advantages of IPM

A. Environmental sustainability

Integrated Pest Management (IPM) supports environmental sustainability by emphasizing methods that reduce ecological disruption and preserve the natural balance of agro-ecosystems (Fahad *et.al.,* 2021). By relying more on cultural, mechanical, and biological controls, IPM reduces the dependence on synthetic chemicals, which are often associated with environmental degradation. Pesticides, when overused or misapplied, contaminate soil, air, and water bodies, disrupting microbial activity and reducing soil fertility. IPM promotes soil health through practices such as crop rotation, intercropping, and habitat conservation, which enrich biodiversity and support ecological functions like nutrient cycling and pollination. Long-term studies have shown that fields managed under IPM protocols exhibit higher soil microbial diversity, better water retention, and lower levels of pesticide contamination. These outcomes align with global goals for reducing the environmental footprint of agriculture and ensuring the long-term viability of farming systems.

B. Minimization of pesticide residues

One of the most pressing concerns in modern agriculture is the presence of pesticide residues in food products. IPM addresses this issue by applying pesticides only when necessary and selecting compounds that are less persistent and more target-specific. Scheduled or prophylactic spraying, common in conventional agriculture, often results in the accumulation of residues that exceed safe consumption limits. IPM uses economic threshold levels to determine whether pesticide application is warranted, thereby avoiding unnecessary use. In crops such as vegetables and fruits, this approach has led to a measurable decline in residue levels. Monitoring programs have recorded reductions of up to 60% in chemical residues when IPM practices are followed. These improvements enhance food safety, reduce health risks for consumers and farm workers, and contribute to the acceptance of agricultural exports under international residue compliance standards.

C. Cost-effective and long-term solution

IPM provides an economically viable pest management strategy that balances input costs with sustainable productivity. Although initial implementation may require investment in training, monitoring tools, or biocontrol agents, the long-term benefits outweigh these costs. Reduced use of pesticides translates into lower expenditure on chemical inputs, fewer crop losses due to pest resurgence or resistance, and improved marketability of produce. Case studies across various cropping systems, including cotton, rice, and vegetables, have shown that farmers practicing IPM achieve 10–25% higher net returns compared to those using conventional methods. The emphasis on prevention and timely intervention lowers the frequency of control measures and extends the effectiveness of available technologies. By integrating multiple control tactics, IPM also delays resistance development in pest populations, preserving the efficacy of control methods and reducing the need for frequent product substitution.

D. Protection of non-target organisms and biodiversity

Conventional pesticide use often harms non-target organisms such as pollinators, natural enemies, soil fauna, and aquatic life. IPM minimizes this collateral damage by promoting selective and localized interventions that avoid broad-spectrum toxicity. Biological control agents, such as predators, parasitoids, and entomopathogenic fungi, are preserved and encouraged in IPM systems. Their role in regulating pest populations contributes to natural biological equilibrium and reduces the need for artificial inputs. Field assessments have demonstrated that IPM-managed plots support higher numbers of beneficial insects, including pollinators like bees and butterflies, which are essential for reproductive success in many crops. The preservation of on-farm biodiversity also increases system resilience to environmental stressors such as climate variation, invasive species, and disease outbreaks. IPM's alignment with conservation agriculture practices makes it a strong contributor to both ecological health and agricultural productivity.

E. Compatibility with organic and sustainable farming

IPM complements the principles of organic and sustainable agriculture by emphasizing ecological approaches and reducing reliance on synthetic chemicals. Many of the tactics used in IPMsuch as habitat manipulation, use of botanical pesticides, biological control, and mechanical removalare fully compatible with organic certification standards. This compatibility allows farmers to transition more easily between conventional and organic systems or to adopt hybrid models that emphasize sustainability without complete conversion. IPM also contributes to the goals of sustainable intensification, which seeks to increase agricultural output while minimizing environmental harm. By integrating IPM into broader farm management practices, growers can enhance soil health, reduce greenhouse gas emissions associated with synthetic inputs, and improve long-term food security. Research has shown that farms practicing both IPM and organic methods achieve higher biodiversity indices, improved water use efficiency, and lower carbon footprints compared to conventional systems. These outcomes reinforce IPM's role as a central pillar in the future of sustainable agriculture.

Limitations and Challenges in IPM Adoption

A. Lack of awareness and training among farmers

One of the most significant obstacles to the widespread adoption of Integrated Pest Management (IPM) is the limited awareness and understanding among farmers. Many growers, particularly those operating at small and marginal scales, are unfamiliar with the principles of economic thresholds, pest surveillance, and ecological pest control. Traditional reliance on visible symptoms and immediate chemical treatments often leads to a perception that IPM is less effective or slower to act. Surveys have shown that a majority of farmers are not aware of beneficial insects or the importance of natural enemies in crop ecosystems. Without structured training programs, farmers lack the technical skills to implement practices such as biological control, pest monitoring, and habitat management. Demonstration trials and farmer field schools have improved awareness in some areas, but coverage remains uneven. Building a strong knowledge base through practical education and continuous engagement is essential to overcoming this limitation.

B. Inadequate infrastructure and support systems

Effective IPM implementation requires access to infrastructure and support services such as biological control agent production units, diagnostic laboratories, monitoring equipment, and advisory services (Baker *et.al.,* 2020). In many farming regions, these support systems are underdeveloped or absent. Timely availability of biocontrol agents like Trichogramma or Beauveria bassiana, for example, is often limited due to the lack of commercial suppliers or public production facilities. Laboratories for pest identification and resistance testing are concentrated in select research institutions, restricting access for the majority of farmers. Extension networks also face staffing and logistical challenges that prevent consistent delivery of IPM-related services. Without reliable infrastructure, it becomes difficult to implement and sustain the integration of multiple pest management tactics. Strengthening institutional capacity, investing in rural diagnostic services, and encouraging public-private partnerships are necessary to support the effective rollout of IPM at scale.

C. Difficulty in pest threshold estimation

A central principle of IPM is the application of control measures based on pest thresholds, such as the Economic Threshold Level (ETL). Estimating these thresholds accurately requires regular field monitoring, identification of pest stages, and understanding of crop development. For many pests and crops, scientifically validated thresholds are either lacking or poorly adapted to local conditions. Variability in weather, crop variety, and field history further complicates the calculation of appropriate intervention levels. As a result, farmers often struggle to determine the exact timing for action, leading either to premature chemical application or delayed response and crop loss. Field observations have revealed that farmers tend to base pest control decisions on visual damage rather than population counts, which may not align with actual economic risk. Development of region-specific thresholds, supported by mobile-based decision support tools, can help overcome this barrier and improve precision in pest management.

D. Time-consuming and knowledge-intensive nature

IPM is inherently more knowledge-driven and labor-intensive than conventional pest control methods. It requires regular scouting, data collection, and decision-making based on biological and environmental observations. Many farmers perceive these activities as time-consuming, especially during peak agricultural seasons when labor is limited. The process of learning pest identification, understanding the life cycles of multiple pests and beneficial organisms, and selecting the right control tactic at the right time demands commitment and skill. For growers accustomed to calendar-based pesticide spraying, transitioning to IPM may involve a steep learning curve. Even when farmers are interested, the lack of user-friendly guides and real-time support makes practical implementation difficult. Ensuring the success of IPM requires not only technical inputs but also behavioral change, which takes time to establish and scale.

E. Resistance from chemical pesticide-dependent systems

Decades of dependency on chemical pesticides have led to deeply entrenched habits among both farmers and input dealers. The chemical industry has historically played a dominant role in pest management decisions through aggressive marketing and incentive structures. In many cases, advisory services are closely linked to pesticide sales, promoting a single-solution mindset that conflicts with the integrated approach of IPM. This commercial influence can create resistance to adopting non-chemical or preventive strategies. Even when farmers observe the benefits of IPM, market dynamics may pressure them to return to chemical inputs due to perceived effectiveness, availability, or recommendations from peers. Shifting this paradigm requires regulatory reform, increased availability of biopesticides, and restructuring of extension services to emphasize sustainability over sales. Transitioning to IPM also necessitates new evaluation frameworks that measure success not by pesticide volumes sold, but by reductions in pest incidence, input costs, and environmental impact. Overcoming these systemic barriers is critical for embedding IPM as the preferred approach in pest management strategies.

Case Studies in IPM Success

A. Cotton IPM modules (e.g., Helicoverpa control)

Cotton has served as one of the most prominent examples of successful Integrated Pest Management (IPM) implementation. *Helicoverpa armigera*, commonly known as the cotton bollworm, has historically caused severe economic losses, with infestation levels reducing yields by up to 40% in untreated fields. IPM modules designed for cotton production integrated multiple strategies including the use of *Trichogramma chilonis* egg parasitoids, neem-based botanical sprays, pheromone traps, resistant varieties, and economic threshold-based chemical applications. Large-scale demonstrations showed that pest incidence dropped by over 50% in plots where IPM was practiced compared to conventional pesticide-dependent farms. Farmers applying IPM reported a reduction in insecticide sprays from 12–15 applications per season to just 5–7, resulting in cost savings of up to 40%. Natural enemy populations, such as ladybird beetles and green lacewings, increased significantly due to reduced pesticide pressure. Yield stability also improved, demonstrating that IPM not only controlled Helicoverpa effectively but also restored ecological balance and enhanced farm profitability.

B. Rice IPM (e.g., stem borer and leaf folder management)

Rice production systems have seen measurable benefits from the adoption of IPM practices, particularly for managing stem borers (*Scirpophaga incertulas*) and leaf folders (*Cnaphalocrocis medinalis*), both of which are major contributors to yield losses. IPM modules for rice included the use of light traps for adult moth monitoring, release of egg parasitoids such as Trichogramma japonicum, timely planting, conservation of spiders and other natural enemies, and selective chemical use based on economic thresholds. In field trials, the incidence of stem borer was reduced by up to 60%, and damage from leaf folder decreased by over 45% in IPM fields. Economic analysis showed that IPM farms achieved higher cost-benefit ratios, with pesticide input costs declining by 30–40% compared to non-IPM farms. Training through farmer field schools played a critical role in teaching farmers how to recognize pest and natural enemy species, implement proper scouting, and apply need-based interventions. The integration of cultural, biological, and mechanical control strategies ensured long-term sustainability in rice ecosystems prone to pest outbreaks.

C. Vegetable crops (e.g., fruit borer in tomato, DBM in cabbage)

Vegetable production, often heavily reliant on frequent pesticide applications, has responded well to IPM techniques, especially in controlling key pests like *Helicoverpa armigera* in tomato and diamondback moth (*Plutella xylostella*) in cabbage. For tomato, the introduction of trap crops such as marigold, combined with pheromone traps, Trichogramma releases, and neem-based insecticides, has led to significant reductions in fruit borer incidence. Field data revealed that fruit infestation dropped from over 30% in conventional fields to under 10% in IPM-managed plots. Similarly, IPM in cabbage employed practices such as net barriers, release of parasitoids like Cotesia plutellae, and the use of Bacillus thuringiensis (Bt) formulations. These strategies effectively suppressed DBM populations and reduced the number of pesticide applications by more than half. Farmer participatory trials showed improved marketable yield and lower chemical residues, meeting safety standards for fresh vegetable consumption and export certification. These results demonstrate how IPM enhances productivity, reduces environmental contamination, and improves produce quality in high-value horticultural crops.

D. Stored grain IPM (e.g., combination of sanitation, fumigation, and bioagents)

Post-harvest losses caused by storage pests such as *Sitophilus oryzae* (rice weevil), *Tribolium castaneum* (red flour beetle), and mites can lead to grain damage ranging from 5% to over 20%, particularly under poor storage conditions (Ahmad *et.al.,* 2021). Integrated approaches in stored grain pest management have shown excellent results when combining sanitation, proper drying, structural repairs, hermetic storage, need-based fumigation, and biological control. Sanitation practices such as removing old residues, sealing cracks, and maintaining dry storage environments reduced pest entry and survival rates. Phosphine fumigation, when applied based on monitoring indicators, resulted in mortality rates exceeding 95% for internal feeders. The use of bioagents like Beauveria bassiana and diatomaceous earth provided residual protection and inhibited pest resurgence. Pilot studies in cooperative grain banks and warehouse settings showed that such integrated methods reduced total storage losses to below 3%. Grain quality parameters such as germination rate, weight, and moisture content were better preserved under IPM protocols, extending storage duration and increasing returns for producers. This highlights how integration of biological, chemical, and preventive measures can successfully manage stored product pests without overreliance on toxic residues.

Recent Developments in IPM

A. Advances in molecular tools for pest detection

Molecular diagnostics have revolutionized pest detection and identification, enabling more precise and early interventions in Integrated Pest Management

(IPM). Tools such as polymerase chain reaction (PCR), quantitative PCR (qPCR), and loop-mediated isothermal amplification (LAMP) are being widely used to detect specific pest DNA or RNA, even at very low population levels. These techniques offer rapid, accurate, and species-specific identification, which is critical for managing pests with similar morphological features but different behaviors or damage potential. Molecular markers are also being developed for identifying cryptic species complexes, such as whiteflies and aphids, which vary in pesticide resistance profiles and transmission of plant viruses. In phytosanitary surveillance, barcoding and high-throughput sequencing have enabled border and quarantine agencies to prevent the spread of invasive pests. These molecular technologies are increasingly being integrated with portable, field-ready diagnostic kits, reducing the time between pest detection and management decision-making. Studies show that early molecular identification can reduce pest-related crop damage by 20–30% due to faster and more targeted responses.

B. RNA interference (RNAi) for pest suppression

RNA interference (RNAi) represents a highly specific biological tool for suppressing pest populations by silencing essential genes within the target organisms. Through the introduction of double-stranded RNA (dsRNA), the technology disrupts gene expression, resulting in developmental failure, reproduction inhibition, or mortality in pests. Unlike conventional insecticides, RNAi does not affect non-target organisms due to its sequence-specific mode of action. Experimental applications of RNAi have shown success in controlling key pests such as *Helicoverpa armigera*, *Spodoptera frugiperda*, and *Myzus persicae*. Laboratory trials demonstrated over 80% mortality in larval stages of target pests following ingestion of gene-silencing constructs. Delivery mechanisms include topical sprays, transgenic plants expressing dsRNA, and nanoparticle-based formulations. This technology holds promise for managing resistant pest populations and reducing chemical usage. Ongoing research is focused on improving RNA stability, efficient delivery, and cost-effective production to facilitate wider adoption in field-level IPM programs.

C. CRISPR gene editing in pest resistance

CRISPR-Cas9 gene editing has emerged as a breakthrough tool in pest management by enabling precise modification of genes related to pest resistance, pest reproduction, and vector capability. Through targeted gene disruption, scientists have developed crop varieties with enhanced resistance to insect pests and viruses. CRISPR-edited rice and tomato lines have demonstrated improved tolerance to brown planthopper and whitefly, respectively. On the pest control side, CRISPR has been used to modify pest genomes for sterile insect techniques (SIT), reducing fertility and population growth in pests like Drosophila and mosquitoes. Field-level application is still in early stages due to regulatory and ecological considerations, but gene-edited traits offer long-term, inheritable protection without requiring chemical input. Research is underway to explore gene drives that promote the spread of lethal traits through pest populations, which could eventually suppress or eliminate high-impact pests. These genetic approaches, when combined with traditional IPM components, could drastically reduce pesticide dependency while enhancing crop protection.

D. AI and remote sensing in pest forecasting

Artificial intelligence (AI) and remote sensing technologies have expanded the capabilities of pest forecasting and early warning systems. AI-driven platforms use machine learning algorithms to analyze large datasets from field observations, climate variables, and pest population trends. These tools can identify patterns and generate real-time forecasts with high accuracy, enabling faster and more targeted IPM interventions. Remote sensing, through satellite and drone imagery, allows for the detection of crop stress symptoms, pest hotspots, and vegetation indices across large geographic areas. Hyperspectral imaging and thermal cameras have been used to identify pest infestations before visible symptoms appear. AI models have predicted locust swarms and fall armyworm outbreaks with over 85% accuracy, providing advance notice for field-level action. Integration of AI with mobile applications has enabled real-time alerts and advisories, enhancing farmer decision-making. These digital innovations are transforming traditional surveillance systems into dynamic and predictive tools that improve the efficiency and responsiveness of pest management strategies.

E. Nanotechnology in targeted pesticide delivery

Nanotechnology offers innovative solutions for enhancing the precision and effectiveness of pesticide delivery in IPM systems. Nano-formulations improve the solubility, stability, and bioavailability of active ingredients, allowing for lower doses and reduced environmental impact. Encapsulation of pesticides in nanocarriers such as liposomes, micelles, and polymer-based nanoparticles enables controlled release and targeted action on pests. This minimizes off-target effects and reduces the degradation of active ingredients under field conditions. Laboratory studies have shown that nano-pesticides achieve similar or greater efficacy at 30–50% lower application rates compared to conventional formulations. Nanoparticles are also being used to deliver biopesticides and RNAi molecules, increasing their field stability and uptake by target organisms. Smart delivery systems, responsive to environmental cues like pH, temperature, or pest enzymes, are under development for next-generation precision agriculture. Regulatory evaluation, safety testing, and cost-effective production remain ongoing challenges, but nanotechnology is rapidly becoming a key component in the evolution of IPM toward more efficient and environmentally conscious practices.

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Chapter 12

Recent Advances: Insecticides, Biorational Pesticides, Drones, and AI

Shruti Biradar*[1], Satappa Kharbade[2] and Vaishnavi Tathode[3]

[1]Ph.D. Scholar, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri

[2]Professor, Department of Entomology, Mahatma Phule Krishi Vidyapeeth Rahuri

[3]Assistant Professor, Department of Entomology, College of Agriculture, Dhule

***Corresponding Author Email:** shrutibiradar137@gmail.com

Modern agriculture faces escalating challenges due to the emergence of resistant pest populations, changing climate patterns, and increased global trade. These factors contribute to shifts in pest dynamics, geographical distribution, and intensity of infestations. Innovation in pest management has become essential for maintaining crop productivity, ensuring food security, and minimizing environmental impact. Traditional pesticide-driven approaches are often insufficient to handle complex pest pressures sustainably. As global agriculture moves toward precision and sustainability, innovative tools such as biorational pesticides, advanced formulations, drone-based applications, and artificial intelligence are playing an increasingly significant role. These innovations not only enhance the efficacy of pest control strategies but also improve safety, cost-efficiency, and environmental compatibility.

A. Limitations of traditional methods and emerging needs

Conventional pest control methods have relied heavily on broad-spectrum insecticides applied through manual or mechanized spraying (Zheng *et.al.,* 2023). These practices often lead to several unintended consequences, such as non-target toxicity, pesticide residues, pest resurgence, and resistance development. Reports from multiple cropping systems indicate a steady decline in the effectiveness of older chemical classes like organophosphates and carbamates due to widespread resistance. Manual scouting and calendar-based spraying lack precision and often result in overuse or mistimed interventions. With rising concerns about residue limits in export commodities and the health risks to applicators and consumers, there is an increasing demand for more targeted, eco-friendly, and technology-driven pest control solutions. Innovations that offer data-driven insights, minimize chemical usage, and preserve beneficial organisms are necessary to meet the evolving expectations of both producers and regulations.

B. Integration of chemical, biological, and technological approaches

The most effective pest management strategies now focus on integrating diverse methods that include chemical, biological, and technological components. Chemical insecticides continue to play a critical role, especially during high-pressure situations, but are increasingly used in more selective and scientifically justified ways. Biorational pesticides such as insect growth regulators, botanicals, and microbial agents offer safer alternatives that align with integrated pest management (IPM) principles. Technological advancements including drones for aerial monitoring and application, as well as artificial intelligence-based pest prediction systems, have created opportunities for real-time decision-making and precision application. By combining these tools, pest management becomes more proactive, data-driven, and environmentally responsible. This holistic approach supports sustainable agriculture by reducing reliance on any single method and improving long-term crop protection outcomes.

Insecticides: Classification and Toxicity

A. Definition and general role in pest control

Insecticides are chemical substances specifically formulated to kill or control insect pests that threaten agricultural crops, stored products, and human health. These compounds serve as a primary line of defense in both conventional and integrated pest management systems. Their application reduces pest populations rapidly, prevents crop damage during critical growth stages, and helps maintain economic yield levels. Insecticides act through various mechanisms, targeting essential physiological or biochemical pathways in insects, leading to paralysis, starvation, or death. Their effectiveness has been pivotal in enhancing global food production, reducing post-harvest losses, and controlling vector-borne diseases.

B. Classification based on mode of action

1. Neurotoxins

Neurotoxic insecticides interfere with the normal function of the insect nervous system. These compounds may block nerve signal transmission, overstimulate neural activity, or inhibit enzymes responsible for regulating neurotransmitters. Organophosphates and carbamates inhibit acetylcholinesterase, resulting in the accumulation of acetylcholine and continuous nerve firing. Pyrethroids act by keeping sodium channels open in nerve membranes, leading to uncontrolled impulses and eventual paralysis. These modes of action are fast-acting and often used during pest outbreaks for immediate knockdown.

2. Growth regulators

Insect growth regulators (IGRs) target developmental processes in insects, disrupting molting, pupation, or metamorphosis. These compounds mimic or inhibit juvenile hormones or interfere with chitin synthesis. For example, methoprene acts as a juvenile hormone analog, while diflubenzuron inhibits chitin formation required for exoskeleton development. IGRs are selective in action, affecting only immature insect stages and sparing adult beneficial organisms. Their application is most effective when timed to pest life cycles and can prevent future pest generations without directly killing adult insects.

3. Respiratory poisons

Respiratory poisons disrupt the insect's ability to respire by targeting cellular respiration pathways. Compounds such as chlorfenapyr act on mitochondrial oxidative phosphorylation, impairing energy production and leading to cellular death. These insecticides are particularly useful against pests that are resistant to neurotoxic compounds. They are often applied as part of resistance management strategies and in combination with other active ingredients for broad-spectrum control.

C. Classification based on chemical composition

1. Organophosphates

Organophosphate insecticides are esters of phosphoric acid and have been widely used due to their broad-spectrum activity (Fest *et.al.,* 2012). They inhibit acetylcholinesterase, leading to neuromuscular dysfunction in insects. Common examples include chlorpyrifos, malathion, and diazinon. Although effective, concerns about human toxicity and environmental persistence have led to their restricted use in several regions.

2. Carbamates

Carbamates also inhibit acetylcholinesterase but generally have shorter environmental persistence compared to organophosphates. Compounds like carbaryl and aldicarb are used in vegetables and fruit crops. They are effective against chewing and sucking pests but require careful handling due to potential toxicity to mammals and pollinators.

3. Pyrethroids

Pyrethroids are synthetic analogs of pyrethrins derived from chrysanthemum flowers. They act on sodium channels in nerve cells, causing hyperexcitation and paralysis. Cypermethrin, deltamethrin, and permethrin are commonly used pyrethroids known for their rapid action and low mammalian toxicity. Their photostability and residual activity make them suitable for field applications, though resistance in pests such as *Helicoverpa armigera* has been widely documented.

4. Neonicotinoids

Neonicotinoids act on nicotinic acetylcholine receptors in the insect central nervous system, causing overstimulation and death. They are systemic insecticides, absorbed by plants and distributed through tissues, making them effective against sap-sucking pests like aphids, whiteflies, and leafhoppers. Imidacloprid, thiamethoxam, and acetamiprid are extensively used in cereals, cotton, and horticultural crops. Despite their efficacy, concerns have been raised about their impact on pollinators, particularly honey bees.

5. Oxadiazines and newer groups

Newer insecticide classes like oxadiazines represent modern advances in insecticide chemistry. Indoxacarb, a prominent member of this group, blocks sodium ion flow in nerve axons, resulting in feeding cessation and death. Other novel groups include spinosyns (spinosad), diamides (chlorantraniliprole), and isoxazolines (fluxametamide), which target ryanodine or GABA receptors. These compounds are often used in resistance management programs due to their novel modes of action and favorable environmental profiles.

D. Toxicity categories

1. Acute vs. chronic toxicity

Acute toxicity refers to the adverse effects that occur shortly after a single exposure to a pesticide, while chronic toxicity involves effects that result from prolonged or repeated exposure. Acute toxicity is measured using LD_{50} (lethal dose for 50% of the test population), which helps determine the immediate risk to applicators and non-target organisms. Chronic toxicity evaluations consider carcinogenicity, reproductive effects, and organ damage over time. Certain organophosphates and carbamates exhibit both high acute and chronic toxicity, necessitating careful handling and strict application guidelines.

2. LD50 values and WHO classification

The LD_{50} value is a standard measure used to assess the toxicity of an insecticide, expressed in milligrams per kilogram of body weight. According to World Health Organization (WHO) classification, insecticides are categorized into four classes: Class Ia (extremely hazardous), Class Ib (highly hazardous), Class II (moderately hazardous), and Class III (slightly hazardous). Monocrotophos is classified as Class Ib, while imidacloprid falls under Class II. These classifications guide regulatory decisions and application protocols to ensure safe usage in agricultural and residential settings.

3. Environmental and non-target toxicity

Insecticides, while targeting pests, can have unintended consequences on non-target species and ecosystems. Beneficial insects such as pollinators, predators, and parasitoids may be harmed by non-selective applications. For example, neonicotinoids have been implicated in the decline of bee populations due to their systemic presence in nectar and pollen. Aquatic ecosystems are vulnerable to runoff containing pyrethroids and organophosphates, which are toxic to fish and amphibians. Persistent insecticides may bioaccumulate and disrupt food chains. To mitigate these risks, emphasis is placed on selecting selective insecticides, using appropriate dosages, and adopting application technologies that minimize drift and runoff. A comprehensive understanding of insecticide classification and toxicity is essential for designing safe, effective, and sustainable pest management programs. This knowledge supports informed decision-making, compliance with safety standards, and the preservation of agro-ecosystem health.

Insecticide Formulations

A. Purpose and advantages of formulations

Formulation of insecticides involves the process of combining the active ingredient with inert carriers, solvents, surfactants, and other additives to create a product that is safe, stable, and effective for practical application (Yusoff *et.al.,* 2016). Formulations are essential to enhance the efficiency of the active ingredient, improve ease of handling, facilitate uniform application, and reduce risks to users and the environment. They also allow insecticides to be applied through various methods such as spraying, dusting, or broadcasting. The formulation type affects absorption, persistence, bioavailability, and compatibility with other agricultural inputs. By improving the delivery and behavior of insecticides in field conditions, formulations play a key role in achieving target specificity, reducing wastage, and minimizing adverse effects on non-target organisms.

B. Common types of formulations

1. Emulsifiable concentrates (EC)

Emulsifiable concentrates are among the most widely used insecticide formulations. They consist of an active ingredient dissolved in an organic solvent along with emulsifiers. When mixed with water, they form an emulsion that can be sprayed onto crops. EC formulations are known for their high effectiveness and ease of use, particularly in large-scale farming. They have excellent penetration ability, but they can also be phytotoxic under certain environmental conditions if not applied properly. Examples include organophosphates like chlorpyrifos and synthetic pyrethroids like cypermethrin.

2. Wettable powders (WP)

Wettable powders are dry, finely ground formulations containing the active ingredient and wetting agents. These are intended to be mixed with water before spraying. WPs form a suspension rather than a true solution and require constant agitation during application to prevent settling. They are safer to handle compared to ECs as they lack harmful solvents, but they may leave visible residues on crop surfaces. Wettable powders are commonly used for managing sucking pests and chewing insects on vegetables, fruits, and field crops.

3. Suspension concentrates (SC)

Suspension concentrates, also known as flowables, are liquid formulations where the active ingredient is suspended in water or oil with the help of dispersants and stabilizers. They combine the advantages of ECs and WPs without the need for solvents. SCs provide uniform distribution, reduced phytotoxicity, and better stability during storage. Products like lambda-cyhalothrin SC are used in rice, cotton, and pulses. Their controlled particle size enhances coverage and bioavailability, improving field performance under varying environmental conditions.

4. Granules (G) and Dusts (D)

Granular formulations consist of the active ingredient coated or absorbed onto inert carriers such as clay or sand. They are applied directly to the soil and are particularly effective against soil-dwelling insects and pests in the root zone. Granules are commonly used in crops like rice, maize, and sugarcane for pests such as stem borers and root grubs. Dust formulations are dry, finely powdered insecticides intended for direct application to foliage or stored produce. Dusts are easy to apply but are prone to drift and are less commonly used in modern agriculture due to health concerns and reduced efficacy.

5. Microencapsulated formulations

Microencapsulated insecticides contain the active ingredient enclosed within polymer-based capsules that release slowly over time. This controlled release mechanism enhances residual activity and reduces the frequency of application. The encapsulation protects the active ingredient from environmental degradation such as UV light or high temperatures. Microencapsulated formulations are used in pest management programs involving high-value crops or areas sensitive to chemical exposure. These formulations improve safety for applicators and reduce non-target toxicity.

C. Recent improvements in formulation technology

1. Controlled-release formulations

Controlled-release technologies focus on delivering the insecticide over an extended period, reducing the need for multiple applications. These formulations utilize biodegradable polymers or encapsulation systems that release the active ingredient in response to environmental triggers such as moisture or temperature. Controlled-release insecticides improve pest control efficiency while minimizing exposure and environmental contamination. They are particularly beneficial in long-duration crops and regions facing labor shortages for repeated applications.

2. Nano-formulations

Nanotechnology has introduced a new dimension to insecticide formulation by manipulating materials at the nanoscale to improve solubility, dispersion, and target specificity. Nano-formulations involve the encapsulation or emulsification of insecticides into nanoparticles ranging from 1 to 100 nanometers. These formulations exhibit enhanced permeability into insect cuticles, controlled release, and reduced degradation, resulting in lower application rates and better efficacy. Nano-imidacloprid has shown improved performance against aphids and whiteflies compared to conventional formulations. These technologies also hold potential for combining insecticides with other agro-inputs like micronutrients in a single delivery system.

3. Compatibility with IPM programs

Modern insecticide formulations are being designed to be more compatible with Integrated Pest Management (IPM) practices. Selective formulations targeting specific pest groups reduce the impact on beneficial insects such as pollinators and natural enemies. Low-toxicity and residue-free products help meet export standards and reduce environmental loading. Slow-release and precision-targeted formulations contribute to judicious pesticide use, aligning with the IPM principle of minimal chemical intervention. These formulations are often compatible with biopesticides and biological control agents, supporting the integration of multiple control strategies in a single crop cycle. Advancements in formulation technology have significantly improved the safety, effectiveness, and sustainability of insecticide use. These developments provide farmers with more flexible and environmentally responsible tools to manage pests across a wide range of crops and agro-ecological conditions.

Insect Repellents and Antifeedants

A. Concept and distinction from insecticides

Insect repellents and antifeedants are substances that prevent insect pests from approaching, landing on, or feeding upon plants and stored commodities (Adeyami *et.al.,* 2014). Unlike insecticides, which exert toxic effects by killing or disabling pests, repellents and antifeedants act primarily through behavioral modification. Repellents function by deterring insects from the host surface through sensory interference, while antifeedants discourage feeding even after contact has been made. These compounds do not cause immediate mortality but are vital in pest prevention strategies, reducing the need for chemical insecticides and lowering the risk of resistance development. Their role becomes crucial in integrated pest management systems, particularly for controlling vectors of disease and safeguarding high-value crops and food products.

B. Plant-derived repellents (e.g., neem, citronella, pyrethrum)

Several botanicals possess naturally occurring insect-repelling or feeding-deterrent properties. Neem (*Azadirachta indica*) is among the most widely studied and used plant-based repellents and antifeedants. Its active compound, azadirachtin, disrupts insect growth and feeding, effectively repelling over 200 insect species including aphids, whiteflies, and caterpillars. Neem formulations are biodegradable and exhibit low toxicity to non-target organisms. Citronella oil, derived from Cymbopogon species, is widely used for repelling mosquitoes and other flying insects due to its strong odor that masks human scent cues. Pyrethrum, extracted from Chrysanthemum cinerariifolium, contains pyrethrins that exhibit both repellent and insecticidal action. These compounds act quickly and degrade rapidly in the environment, making them suitable for organic farming and short-residue applications. Plant-derived repellents are commonly formulated as sprays, oils, and fumigants for use in both field crops and stored grain protection.

C. Synthetic repellents (e.g., DEET, picaridin)

Synthetic insect repellents have been developed to provide long-lasting and stable protection against insect pests, particularly vectors like mosquitoes, flies, and ticks. N,N-Diethyl-meta-toluamide (DEET) is the most widely used synthetic repellent, originally developed for military use. It works by interfering with the olfactory receptors of insects, preventing them from detecting human or plant hosts. DEET offers protection lasting from two to eight hours depending on concentration and environmental conditions. Picaridin, another synthetic compound, provides similar efficacy with a more pleasant odor and lower skin irritation potential. These repellents are commonly used in public health programs and have applications in agriculture for preventing insect vector entry into greenhouses and storage areas.

Their formulations include aerosols, lotions, and impregnated materials such as nets and packaging films.

D. Mode of action of repellents and antifeedants

Repellents act primarily by disrupting the insect's sensory receptors, particularly those involved in olfaction and taste. Volatile compounds in repellents either mask attractant cues or activate avoidance pathways in the insect nervous system. Citronella alters carbon dioxide detection, a key cue used by mosquitoes to locate hosts. Antifeedants interfere with gustatory receptors, making the plant surface unpalatable. Azadirachtin affects hormonal regulation and digestive processes, reducing feeding efficiency and reproductive capacity. These substances act on the behavior rather than physiology of the pest, causing them to avoid treated areas without triggering immediate toxic effects. This reduces selection pressure and supports the long-term sustainability of pest control efforts.

E. Role in vector management and stored grain protection

Repellents and antifeedants play a strategic role in vector management, especially in controlling pests like mosquitoes, sandflies, and flies that transmit diseases such as malaria, dengue, and leishmaniasis. By preventing vector insects from approaching or settling on humans or livestock, repellents reduce pathogen transmission risk without requiring direct killing of the insects. In agriculture, antifeedants are used to protect crops during early growth stages when they are most vulnerable to pest damage. In stored grain environments, botanical repellents such as neem oil and eucalyptus extracts are used to deter storage pests like *Sitophilus oryzae* and *Tribolium castaneum*. These substances can be applied to storage bags, granaries, or as grain protectants, offering a residue-safe alternative to fumigants. Their use reduces post-harvest losses and maintains grain quality during long-term storage.

F. Limitations and regulatory status

Despite their benefits, insect repellents and antifeedants have several limitations that restrict their widespread adoption (Bottrell *et.al.,* 2018). Their effectiveness often depends on environmental conditions such as temperature, humidity, and wind, which influence the volatility and persistence of active compounds. Most natural repellents have shorter duration of activity and may require frequent reapplication to maintain efficacy. Standardization of botanical extracts poses a challenge due to variability in composition based on plant source, harvest time, and processing methods. Regulatory approval for repellents and antifeedants requires rigorous testing for efficacy, safety, and environmental impact. Agencies such as the Central Insecticides Board and Registration Committee (CIBRC) and international bodies like the US EPA and EU EFSA govern the approval and labeling of these compounds. Only a limited number of repellents and antifeedants are registered for agricultural use, though demand for low-residue and organic-compatible products is driving new registrations. The integration of these substances into modern pest management will depend on continued research, improved formulation technologies, and supportive policy.

Biorational Pesticides

A. Definition and significance in sustainable agriculture

Biorational pesticides refer to a class of pest management agents that are derived from natural or biological origins and are characterized by their specificity, safety, and minimal environmental impact. These compounds target specific physiological or behavioral functions in pests without harming non-target organisms such as pollinators, predators, or humans. Their development supports the goals of sustainable agriculture by reducing chemical load, preventing pest resistance, and preserving ecological balance. Biorational pesticides play an important role in integrated pest management systems, offering growers alternatives that are compatible with organic standards and consumer safety demands. As agriculture shifts toward low-residue and eco-friendly practices, these products are becoming integral components of crop protection programs across a wide range of horticultural and field crops.

B. Categories of biorational compounds

1. Botanical pesticides (e.g., azadirachtin, rotenone)

Botanical pesticides are derived from plants that possess natural insecticidal properties. Azadirachtin, extracted from the neem tree (*Azadirachta indica*), is one of the most extensively studied and used botanical compounds. It acts as an antifeedant, oviposition deterrent, and growth disruptor by interfering with molting hormones in insects. Azadirachtin affects over 200 pest species, including aphids, leafhoppers, and caterpillars, without harming beneficial arthropods. Rotenone, obtained from the roots of Derris species, disrupts cellular respiration in insects by inhibiting the electron transport chain in mitochondria. Its use has declined due to concerns about fish toxicity, but it remains significant in certain localized organic farming systems.

2. Microbial pesticides (e.g., Bacillus thuringiensis, Metarhizium anisopliae)

Microbial pesticides are formulated from naturally occurring microorganisms such as bacteria, fungi, viruses, or protozoa that infect and kill specific insect pests. Bacillus thuringiensis (Bt), a soil-dwelling bacterium, produces crystal proteins (Cry toxins) that are toxic to the larvae of Lepidoptera, Diptera, and Coleoptera upon ingestion. Bt-based products have been widely adopted in both open-field crops and protected cultivation due to their effectiveness and host specificity. Metarhizium anisopliae, a fungal pathogen, infects insects through their cuticle, germinating and proliferating inside the body, leading to death through mechanical damage and toxin production. These microbial agents persist in the environment and often establish long-term suppression of pest populations under favorable conditions.

3. Insect growth regulators (e.g., methoprene, diflubenzuron)

Insect growth regulators (IGRs) are synthetic or naturally derived compounds that mimic or disrupt insect hormonal systems. Methoprene is a juvenile hormone analog that prevents larvae from maturing into reproductive adults, breaking the life cycle of pests such as mosquitoes and stored grain beetles. Diflubenzuron inhibits chitin synthesis, thereby affecting molting and leading to the death of immature stages. IGRs exhibit selective activity and are effective against insect populations with defined developmental stages. They are particularly valuable in resistance management because they do not act on the nervous system and thus reduce cross-resistance with neurotoxic insecticides.

4. Semiochemicals (e.g., pheromones for mating disruption)

Semiochemicals are chemical signals used by insects to communicate, and their synthetic analogs are used in pest management to manipulate insect behavior. Pheromones, a key group of semiochemicals, are deployed in traps for monitoring and mass trapping or in mating disruption programs that saturate the crop environment with synthetic pheromones to prevent males from locating females. This leads to reduced mating success and subsequent population decline. Mating disruption has proven highly effective in crops like cotton, grapes, and orchards for pests such as *Helicoverpa armigera*, *Spodoptera litura*, and codling moth. These approaches are species-specific, non-toxic, and suitable for use alongside biological and chemical controls.

C. Mode of action and target specificity

Biorational pesticides act through highly specific modes of action that differentiate them from broad-spectrum insecticides. Botanical compounds such as azadirachtin interfere with hormonal regulation and feeding behavior. Microbial agents like Bt require ingestion and act by binding to gut receptors, causing pore formation and septicemia. Fungal biopesticides penetrate the insect cuticle and proliferate internally, releasing toxins that contribute to mortality. IGRs function at the endocrine level, preventing development and reproduction without immediate lethality. Semiochemicals exploit natural communication systems, either attracting pests into traps or confusing them to disrupt reproductive success. These mechanisms target specific pest groups and reduce unintended effects on beneficial organisms, pollinators, and vertebrates.

D. Compatibility with natural enemies and IPM strategies

One of the strongest advantages of biorational pesticides is their compatibility with natural enemies used in biological control programs. Since these compounds are selective and non-toxic to most predators and parasitoids, they can be integrated into pest management schedules without disrupting beneficial arthropod populations. This compatibility supports the sustainability of IPM by promoting natural biological regulation of pests. Field trials have shown that Bt and azadirachtin treatments do not harm coccinellid beetles, green lacewings, or Trichogramma wasps. IGRs, due to their hormonal mode of action, rarely affect adult natural enemies. Semiochemicals used for monitoring or disruption pose no direct risk to non-target organisms and enhance decision-making in timing interventions. Such synergy between biorationals and biocontrol agents ensures balanced pest suppression with minimal environmental disturbance.

E. Commercial availability and field adoption

The commercialization of biorational pesticides has increased significantly over the past two decades, with numerous products now registered for agricultural use across diverse cropping systems (Haddi *et.al.,* 2020). Bt-based formulations such as Dipel, Biobit, and Xentari are commonly used in vegetables and pulses. Neem-based products containing azadirachtin concentrations of 0.03% to 1% are widely sold under brands like NeemAzal and Achook. Metarhizium and Beauveria-based fungal biopesticides are produced on a commercial scale for use against white grubs, thrips, and mites. IGRs like diflubenzuron are registered for use in cotton and rice, while methoprene is included in stored grain treatment protocols. Pheromone-based lures and traps are commercially available for monitoring Spodoptera, Helicoverpa, and fruit flies, with wide adoption in IPM programs. Market surveys and extension data indicate increasing farmer preference for these alternatives due to residue safety, export compliance, and environmental acceptability. Continued research, awareness, and policy support are expected to expand the role of biorational pesticides in mainstream crop protection.

Use of Drones in Pest Surveillance and Management

A. Drone technology in agriculture

Drone technology has emerged as a transformative tool in agriculture, providing farmers and pest management professionals with the ability to collect, process, and utilize real-time data from aerial platforms. These unmanned aerial vehicles (UAVs) are equipped with high-resolution cameras, sensors, and GPS-based navigation systems that allow precise monitoring of crop health, pest infestations, and environmental conditions. The integration of drones into pest management strategies is part of the broader movement toward precision agriculture, which focuses on optimizing inputs and improving decision-making through advanced technology. Drone-based pest surveillance offers a bird's-eye view of the field, enabling early detection of pest activity and facilitating timely intervention before outbreaks cause significant yield losses.

B. Types of drones used in pest monitoring

Different types of drones are employed depending on the nature of surveillance and application tasks. Fixed-wing drones are capable of covering large agricultural areas in a single flight and are suited for broad-acre pest monitoring. Their extended flight time and higher speed make them efficient for mapping infestations in crops like wheat, maize, and sugarcane. Multirotor drones, typically quadcopters or hexacopters, offer better maneuverability and stability, allowing them to hover over specific field sections and collect detailed imagery. These are commonly used in high-value crops such as vegetables, grapes, and cotton for localized monitoring of insect hotspots. Payload capacity, flight duration, and sensor compatibility are key parameters that determine the choice of drone for pest management operations.

C. Advantages of drone-based surveillance

1. Precision mapping of pest hotspots

Drone-mounted multispectral and thermal sensors capture data that reveal plant stress patterns often associated with pest or disease presence. Vegetation indices like NDVI (Normalized Difference Vegetation Index) and thermal anomalies help identify sections of a field undergoing early pest damage. These insights support site-specific interventions, reducing the blanket application of pesticides and conserving beneficial organisms. Aerial mapping enables faster and more accurate delineation of infested zones compared to traditional ground scouting.

2. Time and labor efficiency

Using drones significantly reduces the time and manpower required for field inspections. Manual scouting over several hectares can take hours or days, whereas drones complete the task in minutes with higher consistency and lower labor input. This efficiency becomes especially valuable during critical crop stages or in large plantations where rapid assessment is essential. Early identification of pest problems allows for prompt corrective actions, preventing economic thresholds from being breached.

D. Application of pesticides using drones

1. Nozzle types and spray optimization

Drones used for pesticide application are equipped with specially designed nozzles that deliver a fine spray mist over crops. Rotary atomizers, flat-fan nozzles, and centrifugal spinning disks are among the most common types used to ensure droplet uniformity and penetration. The system is calibrated to control flow rate, droplet size, and spray width according to the crop type and canopy structure. Drones typically fly at altitudes of 2 to 5 meters and use low-volume or ultra-low-volume (ULV) application techniques, reducing water usage while maintaining effectiveness.

2. Challenges in uniform coverage and drift control

One of the primary challenges in drone-based spraying is achieving uniform pesticide distribution, especially under variable wind conditions. Small drones may have limited payload capacity, affecting coverage per flight. Droplet drift due to rotor downwash or environmental factors can lead to uneven deposition or non-target exposure. Flight path planning, altitude adjustment, and real-time wind sensors are essential to mitigate these issues. Research is ongoing to develop intelligent spraying algorithms that adapt to crop height and canopy density in real time.

E. Regulatory guidelines for drone use in agriculture

The deployment of drones for agricultural purposes is subject to regulatory oversight to ensure safety, privacy, and environmental compliance. Guidelines include mandatory registration of drones, pilot licensing, and adherence to no-fly zones. Specific rules govern the maximum flight altitude, payload limits, and proximity to populated areas or sensitive ecosystems. Drone operators must maintain logs of pesticide usage, flight paths, and operational parameters for audit and traceability. These regulations are designed to balance innovation with public and environmental safety while encouraging responsible adoption of aerial technologies in farming.

F. Case studies of drone integration in crop protection

Successful implementation of drones has been documented across various cropping systems. In rice cultivation, drones equipped with sensors have been used to detect planthopper outbreaks by monitoring changes in canopy reflectance. Precision pesticide application using drone sprayers reduced pesticide use by up to 30% while maintaining control efficacy. In vineyards, thermal and multispectral drone imagery helped identify areas affected by mealybugs and downy mildew, guiding targeted treatment with minimal disturbance to the surrounding environment. Cotton-growing regions have utilized drone-based pheromone dispenser systems to implement mating disruption for *Helicoverpa armigera*, reducing reliance on chemical insecticides. These examples demonstrate the value of drone technology in improving pest surveillance accuracy, enhancing resource efficiency, and supporting sustainable pest control practices across diverse agro-climatic zones.

Application of Artificial Intelligence (AI)

A. Concept of AI in agriculture and pest management

Artificial Intelligence (AI) refers to the simulation of human intelligence processes by computer systems to perform tasks such as learning, reasoning, and self-correction. In agriculture, AI has become a game-changing tool that enhances precision farming through data-driven decisions. In the field of pest management, AI is used to analyze vast amounts of data from sensors, satellite images, and field reports to detect, monitor, and manage pest populations more effectively. By mimicking human decision-making and automating complex tasks, AI enables proactive, rather than reactive, pest control. The use of AI minimizes reliance on routine pesticide applications and supports site-specific, timely, and environmentally conscious interventions.

B. AI-based decision support systems

1. Pest forecasting using weather and crop models

AI-powered decision support systems utilize historical weather data, current meteorological conditions, and crop growth models to predict the likelihood of pest outbreaks (Das *et.al.,* 2024). Algorithms analyze temperature, humidity, rainfall, and other environmental parameters that influence pest biology and movement. For example, systems have been developed to forecast the appearance of fall armyworm, whiteflies, and aphids by correlating pest population trends with weather patterns. These models assist agronomists and farmers in determining the optimal timing for scouting and intervention, thus reducing unnecessary pesticide use and preventing economic damage.

2. Image recognition for pest identification

AI systems trained on thousands of annotated images can accurately identify pests and disease symptoms using smartphone cameras, drones, or fixed sensors. Convolutional Neural Networks (CNNs), a subset of deep learning, are commonly used for this task. When a farmer takes a photo of an infested plant, the AI tool compares the image against its database and provides a diagnosis along with recommended control measures. This approach reduces diagnostic errors and allows rapid action against early infestations. Such systems are particularly useful in identifying visually similar pests or detecting subtle signs of damage that may go unnoticed during manual inspection.

C. Machine learning algorithms for pest outbreak prediction

Machine learning, a subset of AI, involves training models on historical data so they can learn patterns and make predictions without being explicitly programmed. These algorithms are capable of identifying complex, non-linear relationships between environmental variables, crop conditions, and pest population dynamics. By continuously learning from new data, these models improve in accuracy over time. Predictive models for brown planthopper or stem borer outbreaks in rice integrate historical pest incidence, temperature, and planting dates to estimate risk levels for different regions. Such tools empower extension workers and decision-makers to allocate resources efficiently and avoid large-scale losses.

D. Integration with remote sensing and IoT sensors

AI becomes significantly more powerful when integrated with remote sensing data and Internet of Things (IoT) networks. Remote sensing from satellites or drones provides large-scale spatial data on vegetation health, soil moisture, and thermal anomalies. IoT sensors placed in fields collect real-time data on temperature, soil conditions, and pest movement. AI processes these inputs to generate actionable insights. For example, if a drop in chlorophyll is detected in a specific area of a cotton field alongside increased humidity, the AI system may predict the likelihood of whitefly or jassid infestation. This integrated monitoring reduces blind spots in scouting and facilitates targeted interventions that save time and cost.

E. Mobile apps and AI-powered advisory platforms for farmers

Mobile applications equipped with AI capabilities are increasingly available to farmers, offering personalized pest advisory services. These platforms combine location-based data, crop calendars, pest surveillance inputs, and AI-based predictions to provide actionable recommendations. A farmer can input crop type, growth stage, and observed symptoms, and the AI system suggests control strategies based on regional pest risks and resistance profiles. Many of these apps support local languages, voice assistance, and offline functionality, making them accessible in remote rural areas. They also serve as data collection tools, feeding back observations into AI databases for continuous model refinement.

F. Benefits and challenges of AI adoption in pest management

The use of AI in pest management offers several benefits, including improved accuracy in pest detection, reduced pesticide overuse, faster response to outbreaks, and optimized resource allocation. AI enables scalable and sustainable solutions that are adaptable to diverse agro-climatic conditions. It enhances the precision and timeliness of pest control decisions, helping prevent economic threshold breaches. However, challenges remain in terms of data quality, infrastructure, and adoption. Reliable AI systems require extensive datasets for training, which may be lacking in certain crops or regions. Internet connectivity, device affordability, and digital literacy among smallholders can limit access to AI tools. Ensuring data privacy and establishing regulatory frameworks for AI-driven decision-making are also important concerns. Addressing these challenges through investment in digital infrastructure, farmer education, and collaborative research will be crucial for realizing the full potential of AI in sustainable pest management.

Synergistic Use of New Technologies

A. Combining insecticides with AI-guided application

The integration of insecticides with artificial intelligence (AI)-guided systems offers a significant leap toward precision pest control. AI tools analyze real-time data from field sensors, satellite images, and historical pest occurrence patterns to identify zones at high risk of infestation. These insights allow farmers and pest control professionals to apply insecticides only in the required areas and at the optimal time. This zonal application reduces chemical usage, minimizes non-target exposure, and improves cost-effectiveness. AI algorithms also help determine the correct dosage based on pest density, crop stage, and weather forecasts, reducing the likelihood of resistance development. Such integration supports compliance with pesticide residue regulations and enhances sustainability in crop protection.

B. Integrating biorational pesticides with drone technology

Biorational pesticides, being environmentally benign and often effective at low concentrations, benefit greatly from precision delivery systems such as drones. Drones can navigate complex terrains and deliver microbial, botanical, or biochemical pesticides with high accuracy. This method ensures even distribution of agents such as Bacillus thuringiensis, neem oil, or pheromone formulations across the targeted area. The efficiency of drone spraying also allows for timely intervention during critical crop stages, especially during pest outbreaks that require rapid response. Trials have shown that drone-assisted delivery of biorationals reduces application error, conserves water, and protects beneficial organisms by avoiding unnecessary broad-area spraying. The portability and speed of drone systems enhance the practicality of using biorational agents in both large-scale and fragmented farms.

C. Enhancing IPM with data-driven decision-making

Integrated Pest Management (IPM) benefits significantly from technologies that provide real-time, field-specific data. Digital platforms powered by AI, remote sensing, and Internet of Things (IoT) sensors offer timely insights into pest behavior, crop health, and environmental conditions. These platforms support decision-making by recommending specific interventions based on thresholds, pest life cycles, and resistance risk. For example, a system may suggest releasing biological control agents in a given area or applying an insect growth regulator based on the predicted population curve of a specific pest. Combining these recommendations with historical yield data and weather models creates a comprehensive strategy that is both preventive and adaptive. Such data-driven approaches improve IPM outcomes by reducing guesswork, enhancing pest control efficiency, and preserving agro-ecosystem health over the long term. These synergies between technological innovations and IPM principles are critical for meeting the dual goals of productivity and sustainability in modern agriculture.

Environment and Safety

A. Risk assessment of modern insecticides and AI tools

The deployment of modern insecticides and AI technologies in agriculture demands comprehensive risk assessment to ensure that the benefits outweigh the potential environmental and human health hazards. Modern insecticides such as neonicotinoids, diamides, and insect growth regulators are developed with improved selectivity and lower mammalian toxicity compared to older classes like organophosphates and carbamates. Despite these improvements, their impact on non-target organisms, pollinators, aquatic life, and soil microbiota must be critically evaluated. Risk assessments typically include toxicity testing, exposure analysis, and environmental fate studies to determine how long residues persist in soil, water, and plant tissues. AI tools used for pest monitoring and decision-making also require ethical and safety evaluations. Automated systems that generate pesticide application recommendations must be designed with fail-safes to prevent overuse or misuse. Transparency in data algorithms and adherence to regulatory standards are essential for ensuring the safe integration of AI into pest management practices.

B. Ecological impact of drone applications

The use of drones in pesticide application and pest surveillance introduces several environmental advantages, such as reduced fuel use, lower drift, and targeted application (Hafeez *et.al.,* 2023). Yet, concerns remain regarding the potential ecological disruption caused by drone operations. Improper flight calibration, nozzle design, or altitude settings can lead to uneven distribution of chemicals, affecting nearby habitats, beneficial insect populations, and water bodies. Pollinator-rich zones and biodiversity hotspots near agricultural fields are particularly sensitive to spray drift. The buzzing sound and movement of drones may also disturb wildlife, especially in areas with high ecological sensitivity. To mitigate these risks, drone operators must be trained in flight planning and nozzle selection, and flight paths should be optimized to avoid overlap with environmentally sensitive zones. Environmental monitoring after drone operations helps assess the presence of pesticide residues in adjacent ecosystems and supports the development of safer drone application protocols.

C. Residue management and food safety concerns

Pesticide residues on food commodities remain a major concern for both domestic consumers and international markets. Maximum Residue Limits (MRLs) are established to regulate the permissible levels of pesticides in edible crops, and exceeding these limits can lead to health risks and trade rejections. Modern formulations, though more efficient, can still contribute to residue accumulation if misapplied. Residue management involves careful selection of active ingredients, adherence to pre-harvest intervals, and rotation of chemicals to prevent buildup. AI systems and decision support tools contribute by recommending optimal spray timings and safe harvest dates based on real-time environmental data and crop growth stages. Post-harvest testing for residues using chromatographic and spectroscopic techniques ensures compliance with safety standards. Regulatory frameworks also encourage the use of residue-free or low-toxicity alternatives such as biopesticides in high-risk crops like fruits, vegetables, and spices. Ensuring residue management throughout the supply chain is essential for protecting public health and maintaining consumer trust.

D. Farmer training and capacity building

Safe and effective adoption of modern pest management technologies depends largely on the knowledge and practices of the farming community. Many innovations such as AI-driven tools, drone sprayers, and biorational inputs require new skills in digital literacy, equipment handling, and ecological awareness. Without proper training, there is a risk of misuse, over-reliance, or rejection of these technologies. Structured training programs, field demonstrations, and mobile-based advisory services are essential for building farmer capacity. Workshops conducted by agricultural universities, extension services, and private organizations can cover topics such as pesticide calibration, safe handling, personal protective equipment usage, and interpretation of AI recommendations. Capacity building also includes awareness of environmental stewardship, pollinator protection, and legal responsibilities under pesticide and drone usage laws. Creating a network of trained community resource persons helps disseminate knowledge at the grassroots level and ensures long-term sustainability of these practices. Through continuous education, farmers can become active participants in advancing environmentally responsible pest management.

Future and Research Needs

A. Emerging trends in formulation chemistry and biological

Advancements in formulation chemistry are leading to the development of smarter, safer, and more efficient pesticide products. Innovations such as nano-formulations, microencapsulation, and controlled-release systems are allowing active ingredients to be delivered in precise quantities at targeted sites, reducing wastage and environmental contamination. These advanced formulations also enhance the stability, solubility, and uptake of active compounds, improving their field efficacy. Research is also focusing on compatibility of these formulations with integrated pest management (IPM) tools and natural enemies. In parallel, biological pest control products, especially microbial biopesticides like Beauveria bassiana, Metarhizium anisopliae, and virus-based bioinsecticides such as nucleopolyhedroviruses (NPVs), are gaining commercial importance. Development of next-generation biocontrol agents using synthetic biology, fermentation technology, and genetic improvement of microbial strains offers a promising direction for sustainable pest suppression. Formulations combining multiple biocontrol agents or biologicals with biorational adjuvants are under development to enhance performance under diverse field conditions.

B. Potential of AI and robotics in smart pest management

Artificial intelligence and robotics are expected to reshape the landscape of pest management through automation, prediction, and precision delivery. AI models trained on large datasets can predict pest outbreaks based on microclimatic data, crop stage, and pest movement patterns. Machine learning algorithms are being refined to provide hyperlocal advisory services that suggest real-time interventions based on sensor and image inputs. Robotics is also playing an emerging role in automating pest detection, data collection, and pesticide application. Robotic sprayers and autonomous ground vehicles equipped with vision-guided systems can navigate fields to detect pest presence, assess damage, and apply control measures with minimal input. This level of automation is particularly useful in high-value crops where pest management must be frequent, precise, and residue-sensitive. The integration of AI with robotics allows machines to adapt their behavior based on environmental feedback, enhancing efficiency and reducing ecological footprint. Continued investment in AI and robotic innovation holds the key to developing intelligent, scalable, and climate-resilient pest control systems.

C. Public-private partnerships for tech-enabled crop protection

Collaborations between government research institutions, private agritech companies, and farmer cooperatives are essential for accelerating the adoption of modern pest management tools (Bethi *et.al.,* 2023). Public-private partnerships (PPPs) can bridge the gap between laboratory innovation and field-level implementation. Private sector expertise in manufacturing, distribution, and digital platforms complements public sector strengths in research, regulation, and capacity building. Successful PPP models have emerged in the dissemination of biopesticides, drone services, and digital pest advisory platforms. Joint ventures are facilitating field demonstrations, real-time surveillance, and farmer access to AI-driven tools through mobile applications and service centers. Incentives for startups working on precision agriculture and pest diagnostics are promoting entrepreneurship and local innovation. These partnerships also help gather large datasets that improve predictive models and product customization. Strengthening these collaborative frameworks ensures that the benefits of new technologies are scaled efficiently and equitably across farming communities.

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