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# Beyond Pesticides: Innovations in Integrated Pest Management, Pheromone Traps and Biopesticides for Healthy Crops

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## INTRODUCTION

Crop protection is an essential component of agricultural production because insects, mites, pathogens, weeds and other organisms can cause substantial losses before and after harvest. For many decades, synthetic pesticides have been one of the principal tools used to protect crops from damaging organisms. Their rapid action, convenience and broad-spectrum activity have contributed substantially to agricultural productivity. However, repeated and inappropriate pesticide use can create ecological and economic problems.

The development of pesticide resistance is one of the most important consequences of intensive pesticide use. Insect populations exposed repeatedly to the same mode of action can gradually develop resistance, making previously effective products less useful. Repeated pesticide application can also eliminate natural enemies that normally suppress pest populations. This may lead to pest resurgence or secondary pest outbreaks. Integrated pest management provides an alternative framework. Rather than relying on one control method, IPM combines several compatible tactics and uses pest monitoring and economic decision-making to determine when intervention is necessary. Kogan (1998) described IPM as an ecological approach to managing pest populations and emphasized its development around the principles of agroecosystem management, monitoring and integration of multiple control methods.

The Food and Agriculture Organization also identifies monitoring, trapping, resistant varieties, crop rotation, sanitation, biological control, biopesticides and carefully selected chemical measures as components of IPM. Pheromone trapping is particularly valuable because it provides information about pest presence, population trends and seasonal activity before serious damage occurs.

ISSN (E): 2582 – 7022

Modern IPM is now moving beyond conventional biological and cultural techniques toward advanced semiochemical technologies, improved biopesticide formulations, digital pest surveillance, precision application and ecological engineering. These innovations provide an opportunity to develop crop protection systems that protect crops while maintaining ecological balance.

**From Pesticide Dependence to Integrated Pest Management**

The central principle of IPM is that pest management should be based on knowledge of the pest, crop, environment and economic consequences of damage. A farmer should first determine whether a pest is actually present, identify the species and estimate its population. The next question is whether the pest population is high enough to justify intervention. This approach is different from calendar based pesticide application. Under a calendar system, pesticides may be applied at predetermined intervals regardless of actual pest abundance. IPM instead emphasizes surveillance and decision-making.

The major components of modern IPM include:

1. Correct identification of pests and beneficial organisms.
2. Regular monitoring of pest populations.
3. Use of economic thresholds for decision making.
4. Cultural and agronomic practices that reduce pest establishment.
5. Conservation and augmentation of natural enemies.
6. Use of pheromone and other semiochemical technologies.
7. Application of microbial and botanical biopesticides.
8. Mechanical and physical methods where practical.
9. Selective chemical pesticides when other approaches are insufficient.
10. Evaluation of treatment effectiveness after intervention.

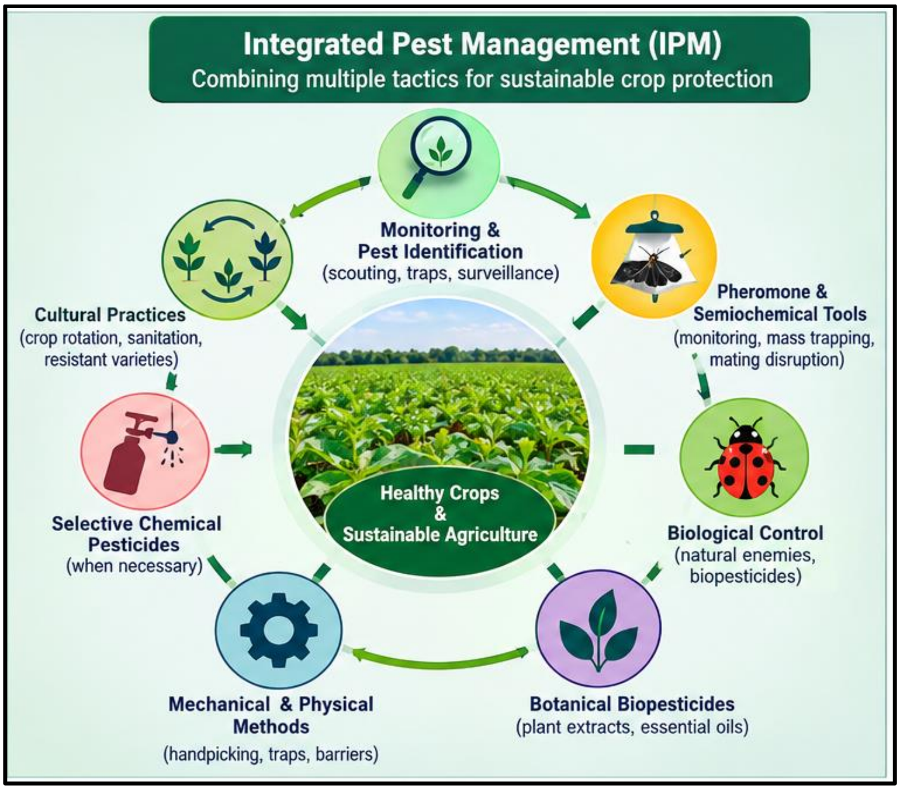


**Figure 1:** Components of integrated pest management (IPM) for sustainable crop protection.

 ISSN (E): 2582 – 7022

**Pheromone Traps as a New Generation Monitoring Tool**

Pheromones are chemical signals produced by organisms that influence the behaviour of other individuals of the same species. In insect pest management, sex pheromones are particularly important because females of many species release chemical signals that attract males. Synthetic versions of these compounds can be incorporated into traps. When a male insect detects the pheromone, it moves toward the source and becomes trapped. The number of insects captured can then be used to estimate pest activity. Pheromone traps therefore have two major functions. The first is monitoring and the second is direct population suppression.

Monitoring is often the most important application. A farmer can detect the beginning of a pest flight and determine whether the population is increasing or decreasing. This information can support decisions about scouting, biological control and pesticide application. Recent reviews have emphasized the species specificity of pheromones and their usefulness in monitoring, mass trapping and mating disruption. Pheromone based approaches can reduce conventional insecticide use and generally have limited direct effects on beneficial organisms because of their high target specificity (Rizvi *et al*., 2021).

**1. Mass trapping**

Mass trapping involves deploying a sufficiently large number of pheromone traps to remove substantial numbers of adult insects from a population. This approach can be particularly useful when pest populations are relatively localized and the target insect responds strongly to the available pheromone. Mass trapping is more effective when trap density, placement, timing and lure quality are carefully managed. Poor trap placement or insufficient trap density may result in monitoring rather than meaningful population suppression.

**2. Mating disruption**

Mating disruption works differently. Instead of physically removing insects, the environment is saturated with synthetic pheromone so that males have difficulty locating females. Successful mating is therefore reduced. This method can be particularly useful against certain moth pests. It is most effective when pest populations are not already extremely high and when immigration from surrounding areas is limited.

**3. Attract and kill technology**

Attract and kill combines an attractant with a toxic substance. The attractant draws the target insect to a treated point or formulation where it receives a lethal dose. This technology extends the concept of pheromone trapping because the objective is not necessarily to retain the insect in a trap. Instead, the insect is attracted to a treatment zone.

Research on attract and kill has also expanded beyond sex pheromones to include plant-derived volatiles and other behavioral attractants. Gregg *et al.* (2018) highlighted the potential of attract and kill systems as components of integrated pest management while noting the importance of attractant selection, formulation and practical field deployment.

**Biopesticides as an Alternative to Broad Spectrum Chemicals**

Biopesticides are pest management products derived from biological organisms or naturally occurring substances. They include microbial pesticides, botanical products, biochemical compounds and other biological agents. Important microbial biopesticides include bacteria, fungi, viruses and nematodes. *Bacillus thuringiensis* is among the best known microbial insecticides and produces proteins that are toxic to susceptible insect larvae. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* can infect insects through the cuticle and are important candidates for biological pest management.

ISSN (E): 2582 – 7022

Biopesticides can offer several advantages over conventional insecticides. These include target specificity, reduced environmental persistence and compatibility with many natural enemy based programs. However, they are not automatically risk free. Their performance depends on formulation, environmental conditions, target pest susceptibility, application timing and storage quality. Recent research emphasizes that successful biological control depends on combining appropriate agents and ecological strategies rather than treating individual biological products as isolated substitutes for conventional pesticides. Galli *et al.* (2024) highlighted the importance of integrating biological control agents with ecological principles and other compatible IPM tactics.

**Microbial Biopesticides and Entomopathogens**

Microbial biopesticides represent one of the most scientifically developed areas of biological crop protection.

**1. Bacterial biopesticides**

*Bacillus thuringiensis* remains one of the most important bacterial insecticides. Different strains produce different insecticidal proteins with activity against specific insect groups. This specificity can reduce unnecessary effects on many non target organisms. Other bacterial organisms are also being studied for pest suppression. Recent research has highlighted the biodiversity of bacterial biopesticides and their potential contribution to sustainable agriculture.

**2. Entomopathogenic fungi**

Fungal pathogens such as *Beauveria*, *Metarhizium* and *Isaria* infect insects through direct contact. Unlike many conventional insecticides that require ingestion, fungal pathogens can penetrate the insect cuticle. Their effectiveness depends strongly on humidity, temperature, ultraviolet radiation and insect susceptibility. Therefore, application should be timed according to environmental conditions.

**3. Viral biopesticides**

Baculoviruses are highly specific pathogens of insects and have been developed as biological insecticides against several important lepidopteran pests. Their high specificity makes them attractive for conservation of beneficial insects, although their relatively slow action can influence farmer acceptance.

**Botanical Biopesticides**

Plants produce thousands of secondary metabolites that can influence insect feeding, development, reproduction and behaviour. Some of these compounds have been developed as botanical insecticides. Neem is one of the best known examples. Azadirachtin can interfere with insect feeding, growth and development. Pyrethrum provides another important example of a plant-derived insecticide. Essential oils and plant extracts are also being investigated for insecticidal, repellent, antifeedant and oviposition deterrent properties. Isman (2020) noted that neem and pyrethrum remain important botanical insecticides while essential oils continue to attract attention as potential crop protection products. However, formulation, consistency, regulatory requirements and field performance remain important limitations.

**Combining Pheromones with Biological Control**

One of the most promising directions in modern IPM is the combination of semiochemicals with biological control. Pheromone traps can indicate when pest populations are increasing. This information can then be used to determine the timing of biological control interventions. Semiochemicals may also influence the behavior of natural enemies. Plant volatiles and other chemical signals can attract parasitoids and predators to areas where pest populations are developing.

Research on interactions between biological control agents and semiochemicals suggests that these approaches can complement one another. Semiochemicals can help manipulate pest and natural enemy behavior, while biological control agents provide sustained suppression of pest populations. This combination is especially valuable because it changes the objective from simply killing pests to manipulating the ecological interactions that determine pest abundance.

## Integration of Major IPM Technologies

**Table 1:** Major innovations and their roles in modern integrated pest management

| IPM innovation | Primary function | Major advantage | Important consideration |
|---|---|---|---|
| Pest scouting | Detect and identify pests | Supports timely decisions | Requires regular field observation |
| Pheromone traps | Monitoring and population suppression | Species specific and sensitive | Correct lure and trap placement are essential |
| Mass trapping | Remove adult pests | Can reduce pest population without broad pesticide use | Requires adequate trap density |
| Mating disruption | Interfere with reproduction | Reduces successful mating | Most effective at appropriate pest densities |
| Attract and kill | Attract pests to a toxic point | Combines behavioral manipulation with control | Requires effective attractant and formulation |
| Biological control | Suppress pests through natural enemies | Conserves ecological processes | Sensitive to pesticide compatibility |
| Microbial biopesticides | Infect or intoxicate target pests | Often selective and environmentally compatible | Field performance depends on environmental conditions |
| Botanical insecticides | Repel, deter or kill pests | Provides natural product options | Formulation and consistency can be limiting |
| Precision monitoring | Detect pest distribution and timing | Reduces unnecessary interventions | Requires technology and technical knowledge |
| Selective chemical control | Control pests when necessary | Rapid and reliable action | Should be used carefully to delay resistance |

## Role of Economic Thresholds

An important principle of IPM is that the presence of a pest does not automatically mean that pesticide application is necessary. Economic thresholds help determine when control action should be initiated to prevent pest populations from reaching economically damaging levels. Thresholds may be expressed as insects per plant, insects per leaf, trap captures per unit time, percentage damaged plants or other suitable measures. Pheromone traps can strengthen threshold based decision-making because trap catches provide quantitative information about pest activity.

The integration of pest counts, crop stage, weather conditions, natural enemy abundance and expected crop value can make decision-making more accurate.

ISSN (E): 2582 – 7022

**Biopesticide Formulation and Delivery Innovations**

One of the major limitations of biopesticides has historically been inconsistent field performance. Microbial agents may be sensitive to ultraviolet radiation, temperature, humidity and rainfall. Botanical compounds may degrade rapidly or have poor water solubility. New formulation technologies are therefore becoming important. Encapsulation can protect active ingredients from environmental degradation and provide more controlled release. Improved carriers can increase adhesion to plant surfaces. Oil-based formulations may improve coverage and persistence of some microbial agents. Recent research has emphasized formulation and delivery as major factors determining the practical success of biopesticides. Current innovations include microencapsulation, improved suspension systems, oil dispersions and nano enabled delivery approaches. These technologies may make biological products more reliable under field conditions and improve their compatibility with commercial crop production.

**Resistance Management Through IPM**

Pesticide resistance is an evolutionary process. When a population is exposed repeatedly to the same selection pressure, resistant individuals can survive and reproduce. IPM can slow resistance development by reducing unnecessary pesticide exposure and combining control methods with different modes of action. Pheromone based methods are particularly attractive because their behavioral mode of action differs fundamentally from conventional insecticidal toxicity. Similarly, biological agents can introduce additional selection pressures. However, resistance can develop against some biological and behavioral technologies as well. Therefore, monitoring and rotation remain important. The goal should be to avoid dependence on any single control mechanism.

**Future Prospects**

- The future of IPM will increasingly involve integration rather than replacement. Synthetic pesticides are unlikely to disappear completely from agriculture, but their role can become more targeted and strategic.
- Future IPM systems may combine automated pheromone traps, artificial intelligence based insect recognition, weather forecasting, biological control, microbial biopesticides, botanical products, resistant crop varieties and precision application.
- Semiochemical research is also expanding beyond traditional sex pheromones. Plant volatiles, aggregation pheromones and other behavioral signals may provide additional opportunities for manipulating pest movement and natural enemy behaviour.
- Research on attract and kill systems demonstrates how chemical ecology can be converted into practical pest management technologies.
- Similarly, advances in formulation science can improve the persistence and reliability of biological products. Recent reviews emphasize that improved formulation and integration with other IPM components will be important for expanding the role of biopesticides in sustainable agriculture.
- The future will therefore depend on interdisciplinary research involving entomology, ecology, chemistry, microbiology, molecular biology, agronomy, engineering, data science and economics.

## CONCLUSION

Modern integrated pest management provides a sustainable alternative to excessive dependence on synthetic pesticides by combining pest monitoring, pheromone technologies,

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biological control and biopesticides with selective chemical interventions. Pheromone traps, attract and kill systems and improved biopesticide formulations can enhance pest suppression while reducing impacts on beneficial organisms and the environment. The future of crop protection will depend on integrating these approaches with precision monitoring, artificial intelligence and ecological management to develop effective, economical and climate-resilient pest management systems.

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