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Insecticide Resistance: Mechanisms, Impacts and Control Strategies

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Abstract

Since, last few years in India insecticide resistance poses a significant threat to agricultural productivity, with resistant pest populations causing up to 30% crop loss annually. The mechanisms of resistance that enable insect population to withstand insecticide application include metabolic detoxification, target site insensitivity and behavioural alterations. This resistance increases the need for insecticides, which accelerates the current problem by decreasing the effectiveness of chemical control measures. The impacts are far-reaching, including higher production costs, environmental degradation and health risks to humans and wildlife. Effective control measures, such as genetically resistant crop varieties, integrated pest management approaches, rotating insecticides with diverse modes of action and refugia to maintain susceptible pest populations are crucial in the fight against insecticide resistance.

Keywords: Insecticides, Mechanisms, Resistance, Resistance management

Introduction

Insecticide resistance is a heritable change in the susceptibility of insects to withstand exposure to a standard dose of insecticide, resulting from physiological or behavioural adaptations (Hawkins *et al.*, 2019). When insect populations come in contact to the same insecticide or group of insecticides having identical mode of action on a regular basis, resistance develops. Physiological and biochemical changes in insect body led to the reduced cuticular penetration, modified target sites with decreased sensitivity to insecticides and enhanced detoxification by over-expression of metabolic enzymes constitute key mechanisms of resistance. It has also been observed recently that resistance mediated through epitranscriptomic processes leading to unanswered concerns regarding the emergence and practical application of insecticide resistance. To develop effective resistance management strategies, it is essential to understand field levels of resistance, the frequency of alleles, genetics, fitness costs and the biology and ecology of resistant populations.

History of Insecticide Resistance

Insecticide resistance was first documented in San Jose scale insect (*Quadrispidiotus perniciosus*), was able to survive under a crust of dried sulfur-lime spray. These insects were able to survive under a "crust of dried spray" composed of sulfur-lime. A decade after the discovery of DDT's insecticidal properties, houseflies were found to be resistant to it in 1947. The singhara beetle (*Galerucella birmanica*) was the first insect pest in India reported to be resistant to BHC and DDT (Pradhan *et al.*, 1963). Subsequently, the red flour beetle, *Tribolium castaneum* became the first pest of stored grains to be resistant to both DDT and Malathion.

Insecticide Resistance Mechanisms

Resistance mechanisms in insects, which develop across generations of spraying, can be broadly categorized into pre-adaptive and post-adaptive mechanisms, reflecting changes that occur either before or after insect populations are exposed to insecticides (Figure 1).

a) Preadaptation

The preadaptive nature of insecticide resistance to pesticides refers to the low frequency of the genes governing the resistance mechanism in the population before any insecticide application (Simon, 2015). Resistance resulting from changes in a single gene is known as monogenic inheritance. For instance, a single incompletely dominant chromosomal factor was responsible for the Colorado

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potato beetle, *Leptinotarsa decemlineata* resistance to azinphosmethyl. Whereas several genes, each with minor cumulative impact, instead of an individual gene with immense effect, govern polygenic Inheritance. At least five genes were involved in the incomplete dominance of dimethoate resistance to Danish strain of housefly, *Musca domestica*.

b) Postadaptation

It describes the changes and modifications that insects go through once they have primarily adapted to insecticide exposure. These defense mechanisms may consist of additional physiological, biological or mutations in the genome that improves the insect's resistance to insecticides.

Behavioural Resistance

Insects resistant to poisons may detect danger and avoid it. When exposed to insecticides, they might stop feeding or move away from sprayed areas. For example, mosquitoes insensitive to DDT often avoided resting on DDT deposits or rested briefly before leaving. Resistant diamondback moths exhibit leg autotomy, shedding their metathoracic legs when they come into tarsal contact with fenvalerate residues (Simon, 2015).

Physiological Resistance

Physiological insecticide resistance mechanisms refer to the biological alterations within insects that allow them to survive exposure to insecticides. Mutations in the nervous system, metabolism and cellular functions are among the various stages at which these changes can occur.

i) Penetration Resistance

It's possible that resistant insects receive the poison far more slowly compared to susceptible ones. The development of barriers in an insect's outer cuticle may restrict the absorption of substances into their bodies. It has been recorded that deltamethrin resistance in Pakistani and Chinese strains of the cotton bollworm, *Helicoverpa armigera* was largely caused by delayed cuticular penetration.

ii) Target Site Insensitivity

It highlights the genetic alterations in the insect that modify the composition or functioning of the particular point where an insecticide acts. These modifications limit the insecticide's efficacy by preventing it from binding to its target site effectively (Simon, 2015).

- *Nerve Insensitivity*: The avermectin sensitivity of *Drosophila melanogaster* was ten-fold reduced due to the P299S mutation, which was found at the C-terminus inside the TM2 domain of the glutamate-gated chloride channel.

- *Altered Acetylcholinesterase (Insensitive AChE)*: In the Mediterranean fruit fly, *Ceratitis capitata* a single point mutation in Acetylcholinesterase (AChE), Gly326Ala, was linked to malathion resistance.

- *Reduction in Midgut Target Site Binding*: A mutation in the BtR-4 gene, which encodes a cadherin protein, has been linked to pink bollworm resistance to *Bt*, reducing the insect midgut's ability to bind the *Bt* toxin Cry1Ac.

- *Mutation in Chitin Synthase*: Sudden change in helix 5 of transmembrane segments of chitin synthase is responsible for resistance to etoxazole in two-spotted spider mites.

iii) Increased Detoxification

Enzymes like cytochrome P450 monooxygenases and glutathione S-transferases (GSTs) are stimulated or activated more when an insect becomes capable to neutralize or eliminate insecticides before they cause an adverse impact. Insecticides are less damaging to insects when they are broken down and metabolized by these enzymes. For example, in the American cockroach, *Periplaneta americana*, GSTs promote organochlorine detoxification. Furthermore, *Drosophila melanogaster* metabolizes DDT to dicofol in the presence of mixed-function oxidase enzymes (Matsumura, 1975).

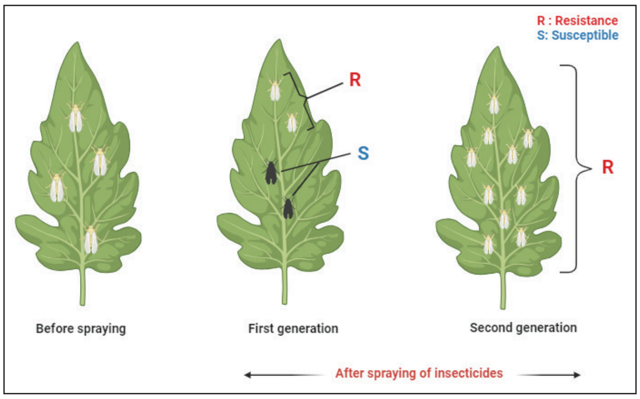

Figure 1: Development of resistance followed by insecticide application

Interaction Phenomena

Cross-resistance occurs when a strain resistant to one insecticide also develops resistance to other insecticides with similar modes of action. For example, *Spodoptera littoralis* showed a 33-fold increase in tolerance to fenvalerate and also exhibited resistance to other pyrethroids and DDT. In contrast, multiple resistances refer to an insect population's ability to withstand exposure to various insecticides with distinct modes of action. For instance, the mosquito species *Culex quinquefasciatus* is resistant to both DDT (an organochlorine) and chlorpyrifos (an organophosphate) (Simon, 2015).

Development Rate of Resistance

Resistance likely starts with the first application of an overdose insecticide, but its development rate may be so slow that it remains unnoticed for years. These factors can be classified into three groups:

- *Genetic Factors*: It includes the integration of the resistance (R) genome with fitness parameters, as well as the frequency, penetrance, expressivity, dominance and association of R alleles.

- *Biological Factors*: It consists of the number of offspring produced in a generation, mating patterns (monogamy versus polygamy), survival and refugia.

- *Operational Factors*: These involve targeted life stages, selection criteria, residue persistence, alternate methods of selection and the chemical composition of insecticides (Simon, 2015).

Insecticide Resistance Management (IRM)

Optimum Dose of Insecticides

Using low or high insecticide doses can spare susceptible individuals and boost resistance evolution due to increased mutation rates in stressed survivors. Thus, balancing doses is crucial, high enough to target most heterozygotes and delay resistance.

Rotation and Chemical Mixtures

Frequently changing insecticides reduces selection pressure and makes resistance less likely. Studies on *Plutella xylostella*, showed slower resistance development over nine generations when indoxacarb, spinosad, dipel were used in each generation compared to using the same insecticide for three consecutive generations.

Use of Synergists

Synergists, which have no insecticidal properties on their own, enhance the effectiveness of insecticides by inhibiting the insect's detoxification mechanisms. For example, combining deltamethrin with piperonyl butoxide (PBO) (1:5) significantly reduced resistance development in *Aedes aegypti* larvae (Simon, 2015).

Use of Transgenic Crops

Genetically resistant crop varieties reduce the need for chemical insecticides and may delay resistance development. Monitoring in *Bt* crop regions, such as with pink bollworm in Arizona and European corn borer in the US has shown less resistance to Cry1Ab, a common *Bt* protein used in these genetically engineered crops.

Use of Newer Insecticides

In the past five years, several newer insecticides have been introduced, including afidopyropen, cyclaniliprole and various pyrethroid esters, *etc*. Advances in pest biochemistry, such as targeting ryanodine receptors, glutamate-gated chloride channels and G-protein-coupled receptors are the key to developing safe and effective new insecticides (Simon, 2015).

Refugia

Refugia in cotton refers to the practice of planting a certain percentage (typically 20%) of non-*Bt* cotton crops alongside *Bt* cotton. The susceptible insects from the refugia can mate with resistant population from *Bt* cotton fields, thereby diluting the resistance genes and slowing the overall development of resistance within the pest population.

IPM Strategies

Regular monitoring and threshold-based insecticide use further support resistance management by ensuring that treatments are applied only when necessary. This holistic approach promotes sustainable pest control while managing resistance.

Conclusion

Insecticide resistance poses a significant challenge to pest management by diminishing the effectiveness of chemical controls. Understanding the mechanisms of resistance, such as genetic mutations and behavioural adaptations, is crucial for developing sustainable strategies, including the use of integrated pest management (IPM), rotation of insecticides and the development of new, targeted treatments. Implementing these strategies can help mitigate the impacts of resistance, ensuring continued agricultural productivity and public health protection.

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