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Pesticide Resistance Management Strategies

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Abstract

Insecticide resistance, the genetic adaptation of insects to withstand chemical treatments, presents a critical challenge to agriculture, public health and pest control. This phenomenon, distinct from insecticide tolerance, evolves over generations due to selective pressure from insecticides, leading to significant implications for pest management strategies. The genetics of resistance, extensively studied in houseflies, mosquitoes and fruit flies, reveal that resistance genes, often at low initial frequencies, become prevalent under selective pressure. Resistance mechanisms include pre-adaptive genetic variations and post-adaptive behavioral and physiological adaptations. These mechanisms allow insects to detoxify, avoid, or tolerate insecticides, complicating control efforts. Effective resistance management strategies such as management by moderation, saturation and multiple attacks are essential. Moderation involves reduced and strategic insecticide use, preserving natural enemies and promoting refugia. Saturation employs high-dose treatments or synergists to target resistant pests selectively. The multiple attack strategy uses rotations and mixtures of different insecticides to prevent resistance buildup. Understanding and implementing these strategies require ongoing research, farmer education and collaboration among stakeholders to ensure sustainable pest management to admit the growing challenge of insecticide resistance.

Keywords Moderation, Multiple resistance, Pre-adaptation, Synergists

1. Introduction

Insecticide resistance happens when insects become immune to the chemicals used to kill them. This resistance is a result of genetic changes that are passed down to future generations. It occurs because insects are exposed to new types of insecticides in their environment. Insecticide resistance is different from insecticide tolerance, which is the ability of insects to withstand the toxic effects of a specific insecticide. Tolerance can develop

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quickly in a population through physiological adaptations, but it can also be lost if insects are no longer exposed to the insecticide.

Pesticide resistance is one of the most significant challenges facing agricultural production, human and animal health protection and structural and industrial pest control. Studies showed that the most resistant species are pests that harm agriculture. However, a significant portion of insects are medically or veterinary important, like mosquitoes and flies. Only a few of resistant species are beneficial, such as predators, parasites and pollinators. Resistance to certain types of insecticides, like cycledienes, DDT and organophosphates, is more widespread compared to other types like carbamate, pyrethroid and fumigant. The high level of resistance to cyclodienes is likely because these insecticides remain active in the environment for a long time.

Resistance is defined as the extra ability of insects to survive exposure to a specific insecticide, even when the dose is not strong enough to eliminate the entire population. The World Health Organization (W.H.O.) describes the definition as "Resistance to insecticides is the development of an ability in a strain of insects to tolerate doses of toxicant which would prove lethal to the majority of individuals in a normal population of the same species". The key word here is "development," which means that this resistance is not natural or inherent in the insect species. It's something that develops over time as a response to the insecticide (Anonymous, 2011).

It's important to note that some insect species are naturally tolerant to certain chemicals, which means they can withstand levels of insecticides that would be deadly to closely related species. This natural tolerance is present in all individuals of that species and doesn't require prior exposure to the chemical.

Resistance can be either low or high. When it's low, it's also called "Vigor tolerance," which means an increased ability to withstand stressful conditions, like exposure to insecticides. Resistance can also be classified as cross or multiple resistance. Cross resistance happens when the same defence mechanism (usually governed by single gene) such as oxidative detoxification, protects against several other insecticides. It's called multiple resistances when an insect strain has resistance to various chemicals due to different defence mechanisms controlled by different genes. If a single gene is involved in resistance development, it's called monogenic resistance. If several genes are involved, it's called polygenic resistance.

Negatively correlated resistance is the opposite of multiple resistances. When resistance to one insecticide (A) is selected, susceptibility to another insecticide (B) is also selected and vice versa. This means that insect species that are not killed by insecticide A can be controlled by insecticide B, allowing for pest suppression over a longer period by alternating the use of the two insecticides. There is some degree of reversion from resistance back to susceptibility when the pressure from an insecticide is removed. However, when the insecticide pressure returns, resistance quickly reappears in the insect population.

2. Occurrence of Resistance

Insecticide resistance is a major problem that is increasing in occurrence. It was first noticed in 1908 when a type of scale insect in Washington State became resistant to a specific chemical. Over time, resistance has been observed in many other insect and mite species. This resistance causes significant economic losses in agriculture and affects human and animal health. It is a big challenge for farming, pest control and protecting structures and industries from pests.

Resistance was first detected in the state of Washington in 1908 when the San Jose scale, *Quadraspidiotus perniciosus*, was found to be resistant to lime sulfur. In 1916, resistance to hydrogen cyanide fumigant was observed in the California red scale, *Aonidiella auranti* and the black scale, *Saissetia oleae*. In 2004, there were 540 species of insects and mites resistant to one or more pesticides.

Resistance occurs when pests, such as insects, become immune or less affected by pesticides that are used to control them. In India, resistance to pesticides was first observed in insects that are important for public health. For example, in 1952, mosquitoes known as *Culex fatigans*, which transmit a disease called filaria, were found to be resistant to a pesticide called DDT in Uttar Pradesh and Bombay. These mosquitoes have since become resistant to both DDT and another pesticide called BHC in different parts of the country (Gupta, 2022).

Other pests like bed bugs, lice and house flies have also developed resistance. In 1952, human body louse called *Pediculus humanus corporis* developed resistance to HCH in hilly areas of the country. In 1953, bed bugs in Pune were found to be resistant to DDT. House flies known as *Musca domestica nebulo* became resistant to DDT in 1957 in Bombay and Assam and now they are resistant not only to DDT but also to BHC throughout India.

Resistance in agricultural pests was first reported in 1963 when singhara beetles called *Gelerucella birmanica* in Delhi were found to be resistant to DDT and BHC. Other pests like *Spodoptera litura*, a type of caterpillar, developed resistance to BHC in Rajasthan. Over time, this pest also became resistant to other pesticides like malathion, endosulfan and carbaryl.

Different cases of resistance have been reported in various pests across the country. For example, the diamondback moth called *Plutella xylostella* became resistant to DDT in Punjab in 1968 and later developed resistance to other pesticides like endrin, parathion, fenitrothion, fenvalerate, cypermethrin, quinalphos and deltamethrin in different states like Delhi, Haryana, Uttar Pradesh, Bihar and Karnataka.

Resistance has also been observed in pests such as *Lipaphis erysimi*, *Heliothis* on cotton, *Tribolium castaneum*, *Sitophilus oryzae*, *Oryzaephilus surinamensis* and *Dermestes granarium* in different parts of the country against pesticides like endosulfan, malathion, lindane, phosphine and synthetic pyrethroids.

Insecticide resistance appeared first in insect pests of public health programme, then in agricultural and storage pests because, a large number of insecticides used under the National Malaria Control Programme from 1948 to 1960 resulted in the development of insecticide resistance in insect vectors of human diseases. In agriculture development of resistance was comparatively appeared later because an appreciable amount of insecticide could be used from 1970 onwards on the agricultural crops raised using high yielding varieties, irrigation, fertilizers and pesticides.

3. Genetics of Resistance

Most of the research conducted on insect resistance has focused on three main insect species: houseflies, mosquitoes and fruit flies (specifically, *Drosophila melanogaster*). These insects were chosen because they are well-suited for studying genetics and biochemistry. Additionally, houseflies and mosquitoes are significant because they can spread serious diseases. By studying these insect species, scientists have gathered evidence that can be applied to understand the genetic mechanisms and resistance to insecticides in other insects as well (Simon, 2011).

3.1. Pre-Adaptation

Resistance to insecticides in insects and mites is something they already have in their genes (pre-adaptive), but in very low frequencies until they are selected again in the present time by the use of insecticides. These genes are like mutants from a long time ago or were selected by other harmful substances in their environment in the past.

Researchers showed that houseflies can develop resistance to DDT by choosing the larvae that took long time to turn into pupae. After doing this for 15 generations, the resistance to DDT was eight times higher than in the original flies. Additionally, a resistant strain of fruit fly, *D. melanogaster* can also be developed by selecting pupae from outside of the larval medium.

3.2. Gene Frequency

Usually, the number of resistance genes in natural populations is quite low, ranging from 0.0001 to 0.01. However, sometimes certain wild populations have a surprisingly high percentage of these resistance genes. For example, before the use of a pesticide DDT, a group of bedbugs in Taiwan was found to have 0.5% of genes that made them resistant to DDT. Similarly, a type of mosquito called *Anopheles gambiae* in Nigeria had 0.4-0.6% of genes that made them resistant to a pesticide called dieldrin. In tobacco budworms, the estimated frequency of genes that provide resistance to a pesticide called CrylAc was 0.0015, while in sugarcane borers, the estimated frequency of genes providing resistance to CrylAb was 0.0023. In Greece, the frequency of genes conferring resistance to CrylAb in a type of moth called *Sesamia nonagrioides* was 0.0032. So, when these populations are exposed to insecticides at a certain level, it's not surprising that they quickly develop a population that is resistant to those insecticides.

In populations that are already resistant, the frequency of resistance genes can be very high. For example, using a specific genetic testing method called real-time PCR, researchers found that the frequency of pyrethroid resistance allele ranged from 0.25 to 0.966 in 11 field populations of a mosquito called *Anopheles sinensis* in Korea. This indicates that resistance to pyrethroids in these mosquitoes is widespread.

3.3. Dominance and Number of Genes

Resistance genes determine an organism's susceptibility to substances or factors. They can be dominant, recessive, incompletely dominant, or incompletely recessive. The type of resistance gene involved varies for specific insecticides. Carbamate and organophosphate resistance is usually dominant or incompletely dominant. DDT, Bt and spinosyn resistance is typically recessive. Dieldrin resistance is usually incompletely dominant, while pyrethroid resistance is incompletely recessive.

In the case of diamondback moths, resistance to permethrin is inherited as an incompletely recessive gene on an autosome, while resistance to methomyl is inherited as an incompletely dominant gene on an autosome. Stone's method (1968) can be used to measure the degree of dominance in offspring. The formula:

$$D = \frac{2X_2 - X_1 - X_3}{X_1 - X_3}$$

Where,

X_1 = Log LD_{50} value for the susceptible homozygote (S);

X_2 = Log LD_{50} value for the heterozygote (RS);

X_3 = Log LD_{50} value for the resistant homozygote (R);

$D = 1$: Complete dominance;

$0 < D < 1$: Incomplete dominance;

$-1 < D < 0$: Incomplete recessively;

$D = -1$: Complete recessively;

$D = 0$: intermediate.

Resistance can be conferred by a single gene, leading to high resistance, or sometimes multiple genes can be involved. Examples include spider mites with organophosphate resistance, western flower thrips with spinosad resistance, houseflies with DDT resistance and certain Diptera species with dieldrin resistance. Carbaryl resistance in houseflies, fall armyworms and malathion resistance in oriental houseflies involve multiple genes.

3.4. Loss of Resistance

This is an important question when planning how to deal with resistance. Resistance happens when certain genes that were rare before become more common due to human intervention. When the pressure that caused the selection is removed, it is expected that the normal characteristics will become common again. Resistance to DDT and organophosphates quickly decreased once the selection pressure stopped. So, some insecticides are more likely to maintain resistance over time compared to others. The stability of resistance depends on various factors like the genetic makeup of the population, the type of selection pressure and the presence or absence of natural selection.

4. Mechanism of Resistance

The development of resistance in insects to insecticides may be due to the genetic variations already exists in the insect population which are screened out by the pressure of insecticides. Such type of mechanism is known as pre adaptive mechanism of insect resistance. The other mechanism is the post adaptive in which resistance may develop due to behavioristic or ecological and/or physiological considerations.

- Pre-Adaptive
- Post Adaptive [(a) Behavioral and (b) Physiological]

4.1. Pre-Adaptive Mechanism

Resistance arises from pre-existing genetic variations within the insect population. Insects with these genetic traits survive and reproduce, leading to a resistant population. Example in Houseflies: Resistance to DDT is linked to the recessive gene *Kdr* (Knockdown resistance) on chromosome 3, which leads to nerve insensitivity. Other genes like *Kdr*-NPR and DDTase contribute to resistance against various insecticides through different mechanisms.

4.2. Post-Adaptive Mechanism

Resistance develops due to changes in behavior or physiological adaptations.

4.2.1. Behavioral Resistance

Insects alter their behaviors to avoid insecticides. Example: *Euxesta notata* avoids areas treated with malathion and parathion. *Anopheles gambiae* mosquitoes avoid houses with DDT deposits (increased exophily).

4.2.2. Physiological Resistance

Insects develop internal mechanisms to detoxify or tolerate insecticides.

- *Lipoid content*: Higher lipoid content in resistant insects absorbs and stores insecticides.
- *Excretion*: Faster excretion rates in resistant insects.
- *Dietary factors*: Diets high in ascorbic acids and lipids can increase resistance.
- *Detoxification*: Enzymes like DDTase break down insecticides into non-toxic metabolites. Example: DDTase converts DDT into DDE. Houseflies resistant to cyclodienes metabolize aldrin into less toxic substances. Enhanced detoxification by phosphatases and mixed-function oxidases also contributes

to resistance in various species.

5. Pesticide Resistance Management Strategies

The approaches to resistance management may be grouped under three headings: management by moderation, management by saturation and management by multiple attack (Georghiou, 1994; Jutsum *et al.*, 1998).

5.1. Management by Moderation

Management by moderation is an approach that acknowledges the importance of genes that make plants resistant to pests. It aims to protect these genes by reducing the use of chemicals that kill pests. Some actions taken in this approach include using lower amounts of insecticides, applying them less frequently, using chemicals that don't persist in the environment for a long time and preservation of refugia. These actions are cautious and conservative. However, they often need to be combined with non-chemical methods like using plants that are naturally resistant to pests, planting and harvesting at the right time and promoting the use of natural predators to control pests.

5.1.1. Using Low Doses of Insecticides

Employing smaller amounts of insecticides helps spare susceptible pests and is aligned with sustainable pest control practices. This approach prevents the complete eradication of pests and preserves their natural enemies, ensuring a more balanced ecosystem.

5.1.2. Using Insecticides that Breakdown Quickly

Pesticides with short persistence in the environment minimize the exposure of pests to chemicals. This reduces the selection pressure for resistance as pests have less time to adapt and develop resistance mechanisms.

5.1.3. Use of Predators and Parasitoids

Researchers have observed that resistant predators are more likely to be found in areas where pesticides have been used moderately. This is because when some pests are left alive by the pesticides, the predators still have something to eat. By using these resistant predators and parasites in agricultural fields, we can reduce the frequency of pesticide applications. This, in turn, reduces the pressure on the pests to develop resistance and can help in managing pest populations more effectively.

5.1.4. Use of Transgenic Crops

The key factor delaying resistance in *Bt* crops is the presence of refuges that enable survival of susceptible pests. The initial frequency of resistance alleles is typically low and resistance to *Bt* crops is often inherited in a recessive manner. To ensure the effectiveness of *Bt* crops, the Environmental Protection Agency (EPA) implemented regulations in 1995. These regulations required farmers planting *Bt* cotton to also plant non-*Bt* crops in the same area, creating refuges. The recommended refuge size can vary, but it is often advised to range from 5% to 50% of the total acreage.

While management by moderation is good for the environment and doesn't harm natural pest control methods, it may not be suitable when valuable crops need strong protection, when diseases carried by pests need to be controlled, or when newly introduced pests need to be eliminated. In these situations, other approaches like saturating the pests with treatments or attacking them in multiple ways may be more appealing (Radcliffe *et al.*, 2009).

5.2. Management by Saturation

In simple terms, the term "saturation" doesn't mean filling up the environment with pesticides. It means using a high amount of pesticides to overcome the insect's defenses when they have developed resistance. This approach works better when resistance genes are rare and mostly present in the insect's genetic makeup. There are different ways to deliver high doses of pesticides directly to the target insect.

5.2.1. Using High Doses Selectively

It includes using microencapsulation, attractants, or baited targets that make the insect consume the pesticide at lethal levels, especially when they carry resistance genes in the heterozygous state. This method targets pests carrying resistance genes by applying higher doses of insecticides. By eliminating these pests, the dominance of resistance genes in the population is reduced, slowing down the evolution of resistance. However, caution is necessary to ensure this approach doesn't inadvertently accelerate the selection of resistant pests.

5.2.2. Use of Synergists

It helps in delaying the development of resistance to insecticides. This happens because the detoxification system is blocked by the synergist and making it harder for the insect to survive. However, this method won't work if the insect has other ways to detoxify pesticides. As a result, insects with genes that give them metabolic resistance would die in the same proportion as susceptible ones. This greatly reduces the chances of resistance developing. For example, selecting larvae with a combination of deltamethrin and piperonyl butoxide (PBO) effectively suppressed resistance development in *Aedes aegypti* mosquitoes.

Each of these approaches can be useful in specific situations. Using a moderate strategy would be appropriate in a forest environment, while a saturation tactic might work in a greenhouse, a grain elevator, or with bait sprays, depending on the circumstances.

5.3. Management by Multiple Attacks

The multiple attack approach is the concept that control can be obtained by means of a number of independently acting stresses, such as insecticides, each of which exerts selection pressure below the threshold that could result in resistance. This method involves applying chemicals in rotations and mixes (Anonymous, 1986).

5.3.1. Mixing Different Insecticides

Using a mixture of insecticides can help slow down the development of resistance in insects. When insects are exposed to multiple chemicals at the same time, it becomes harder for them to adapt to all of them simultaneously. The idea is that the resistance mechanisms for each chemical are rare and unlikely to occur together in a single insect. So, if an insect survives one chemical, it will be killed by the other. However, using insecticide mixtures can also have drawbacks. Resistance to both chemicals in the mixture can develop quickly in some cases. Additionally, there may be cross-resistance, meaning that insects resistant to one pesticide may also be resistant to similar pesticides.

5.3.2. Using Different Insecticides in a Rotation

Another approach to combat resistance is by rotating different classes or types of insecticides to control the same pests. This method assumes that by using a different insecticide each time and giving enough time or several generations between the uses of the same insecticide, the frequency of resistance will decrease.

For example, when compound A is applied, resistance to it increases slightly in the following generation but declines in the next three generations when it is not used. Then, when compound A is used again in the fifth generation, resistance rises but declines in generations six to eight. The same pattern is expected for compounds B, C and D. This is because insects that are resistant to a particular chemical often have lower fitness compared to susceptible individuals, meaning they are less successful in reproducing. So, during the interval between applications of the same compound, the frequency of the resistance alleles decreases.

The results have varied depending on the insecticides used and the insects being targeted. The success of each approach depends on many factors, like choosing the right chemicals, understanding how insects can develop resistance and knowing if resistant insects are less fit than susceptible ones.

6. Conclusion

Pesticide resistance poses a significant challenge in agricultural and pest control practices. Understanding resistance mechanisms is crucial to develop effective resistance management strategies. As long as the farmers use the chemicals injudiciously there will be this problem of resistance. So, we have aware the farmers and recommend the authorized IRM strategies. Continued research, education and collaboration among stakeholders are essential for sustainable pest management and safeguarding agricultural productivity in the face of pesticide resistance.

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