



Understanding Pesticide Resistance: Causes, Consequences and Future Solutions

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Pesticides have played a crucial role in improving agricultural productivity and protecting crops from destructive pests and diseases. However, the repeated and excessive use of these chemicals has contributed to a growing global concern, pesticide resistance. Resistance occurs when pest populations gradually adapt to survive treatments that once effectively controlled them. This phenomenon threatens crop production, increases management costs, and reduces the long-term effectiveness of plant protection practices. In countries with intensive agricultural systems, including India, pesticide resistance has become an important challenge for achieving sustainable food production. This article explores the major causes of pesticide resistance, examines its environmental and economic consequences, and discusses practical and future-oriented solutions that support sustainable crop protection. A balanced approach combining scientific innovation, integrated management, and responsible pesticide use will be essential for maintaining agricultural resilience.

Keywords: Crop protection, pest management, pesticide resistance, sustainable agriculture

Introduction

Agriculture has always been closely linked with the ability to protect crops from pests, diseases, and weeds. Since the introduction of synthetic pesticides in the twentieth century, farmers have been able to reduce crop losses and achieve higher yields (Aktar *et al.*, 2009). These chemicals became an essential part of modern agriculture and contributed significantly to food security around the world. Despite these benefits, the long-term dependence on pesticides has created unintended consequences. One of the most serious outcomes is pesticide resistance, a biological process in which pest populations evolve the ability to survive pesticide applications that previously controlled them effectively (Georghiou, 1990). Over time, the surviving individuals reproduce and pass resistance traits to future generations. Today, pesticide resistance affects insects, weeds, fungi, and other agricultural pests across different cropping systems. The challenge extends beyond reduced pesticide performance; it influences production costs, environmental quality, and the sustainability of agricultural systems (Pimentel, 2005). Understanding how resistance develops and identifying practical solutions are essential steps toward protecting future food production.

Understanding Pesticide Resistance

Pesticide resistance is the ability of a pest population to withstand the effect of pesticide that was previously effective in controlling it. It is an inherited adaptation that allows certain pests to tolerate doses of pesticides that once caused effective control (Sparks & Nauen, 2015). Resistance does not occur suddenly. It develops gradually through repeated exposure. Within

any pest population, natural genetic variation exists. When pesticides are applied repeatedly, susceptible individuals are eliminated while naturally tolerant individuals survive. These survivors reproduce and increase the proportion of resistant individuals in subsequent generations. Eventually, the pesticide loses effectiveness.

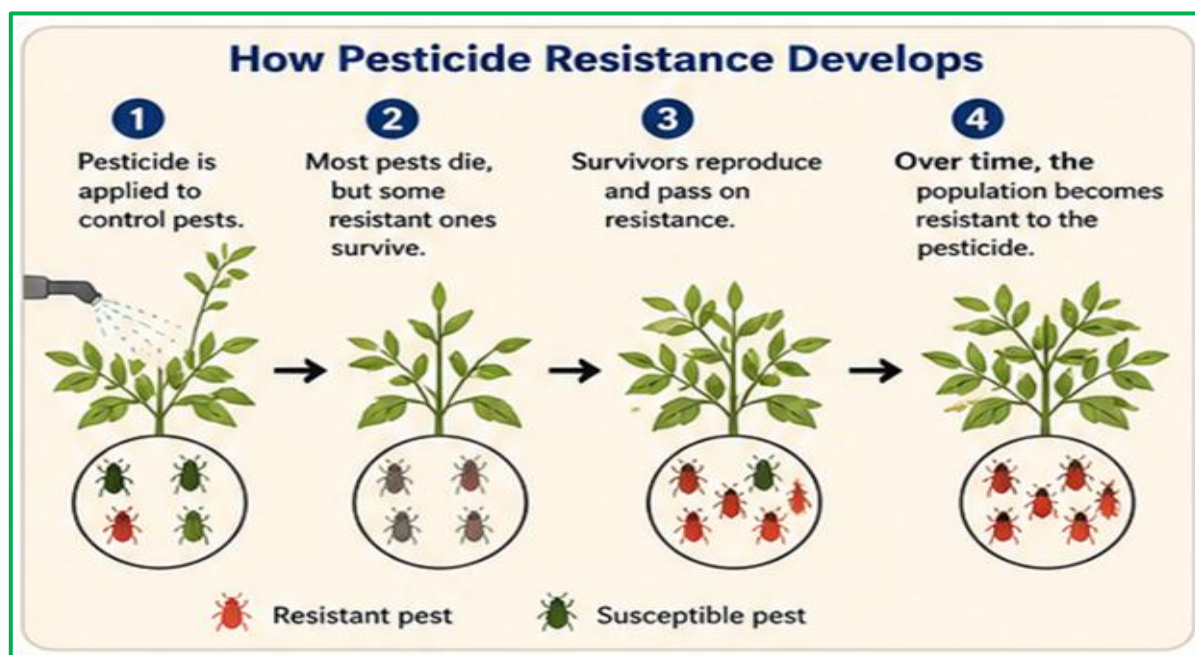


Fig 1. Pictorial presentation on development of pesticide resistance

Resistance can occur in:

- Insect populations (insecticide resistance)
- Weeds (herbicide resistance)
- Plant pathogens (fungicide resistance)
- Rodents and other agricultural pests (WHO, 2020)

The speed at which resistance develops depends on pest biology, pesticide characteristics, environmental conditions, and management practices.

Causes of Pesticide Resistance

- **Repeated Use of the Same Pesticide:** One of the primary causes of resistance is the continuous use of a single pesticide or pesticides with the same mode of action. Repeated exposure places strong selection pressure on pest populations and accelerates adaptation. Example: Repeated spraying of cypermethrin on cotton crops led to resistance in cotton bollworm (*Helicoverpa armigera*).
- **Excessive and Improper Application:** Applying pesticides at higher than recommended doses or using them more frequently than necessary may increase resistance development. Incorrect timing and non-target applications also contribute to ineffective control.
- **Sub-lethal dosages:** Applying diluted or weak concentration fails to kill the entire target population, essentially exposing pests to a small dose that helps them adapt and survive.
- **Monoculture and Intensive Farming Systems:** Growing the same crop repeatedly over large areas creates favourable conditions for specific pests to thrive. Continuous host availability increases pest populations and encourages repeated pesticide use (FAO, 2021).
- **Lack of Integrated Pest Management Practices:** Dependence solely on chemical control reduces the use of alternative methods such as biological control, cultural practices, and crop monitoring, increasing resistance risk.
- **Lack of Refugia:** Treating an entire farm without leaving unprotected “refuge” zones eliminates susceptible pests completely. This prevents them from breeding with and diluting the genetics of the resistant pests.

- **Limited Farmer Awareness:** In some agricultural regions, farmers may lack access to training regarding pesticide rotation, recommended dosages, and resistance management principles.

Consequences of Pesticide Resistance

- **Reduced effectiveness of pesticides:** When pests develop resistance, pesticides no longer kill them effectively. Farmers have to spray more often, but the pests continue to survive and damage crops.
- **Increase in crop losses:** Resistant insects, weeds, or fungi can spread rapidly and destroy agricultural produce, leading to lower crop yield and reduced food production.
- **Higher cost of farming:** Farmers need to buy stronger or larger quantities of pesticides and apply them repeatedly. This increases production costs and reduces profit.
- **Environmental pollution:** Excessive use of pesticides contaminates soil, water bodies, and air. It can disturb ecosystems and reduce environmental quality.
- **Harm to beneficial organisms:** Increased pesticide use may kill useful insects such as bees, butterflies, and natural predators that help control pests, affecting biodiversity.
- **Development of multiple resistance:** Some pests become resistant to several types of pesticides at once, making pest control even more difficult and limiting available treatment options. Example: *H. armigera* has developed widespread resistance to pyrethroids, organophosphates, and Bt (*Bacillus thuringiensis*) toxins.
- **Disturbance in ecological balance:** Pesticide resistance can disrupt the natural balance of ecosystems. As resistant pests survive and multiply, they may outnumber other organisms, leading to changes in food chains and creating long-term ecological problems.
- **Risk to human and animal health:** Higher pesticide usage can leave harmful residues on food and increase exposure for farmers, animals, and consumers, potentially causing health problems.

Solutions for Managing Pesticide Resistance

- **Pesticide Rotation and Mode of Action Diversity:** Rotating pesticides with different modes of action reduces selection pressure and slows resistance development. Strategic use of available products extends their effectiveness. Example: Rotating imidacloprid with spinosad to control whiteflies reduces resistance development because they have different modes of action.
- **Biological Control Approaches:** Natural predators, parasitoids, beneficial microorganisms, and microbial pesticides provide environmentally responsible alternatives to chemical dependency.
- **Development of Resistant Crop Varieties:** Plant breeding and biotechnology have improved crop resistance against pests and diseases. Resistant varieties reduce pesticide demand and support sustainable production. Example IR 62 rice variety against brown plant hopper.
- **Precision Agriculture and Digital Technologies:** Emerging technologies such as remote sensing, drones, artificial intelligence, and decision-support systems enable early pest detection and targeted interventions.
- **Integrated Pest Management (IPM):** Integrated Pest Management offers one of the most effective long-term solutions. It combines multiple strategies including pest monitoring, biological control, cultural practices, resistant varieties, and selective pesticide use. Instead of eliminating all pests, IPM focuses on maintaining populations below economically damaging levels.
- **Maintain Refugia:** Leave localized areas untreated to maintain a population of susceptible pests. This dilutes the surviving population by allowing them to breed with non – resistant individuals (Tabashnik et al., 2013). Planting 20% non-Bt cotton rows around Bt cotton fields to maintain susceptible pink bollworm (*Pectinophora gossypiella*) populations and delay resistance development.

- **Farmer Education and Policy Support:** Farmer training programs, extension services, and public awareness campaigns remain essential for encouraging responsible pesticide use and adoption of sustainable practices.

The Way Forward

The future of plant protection depends on balancing productivity with ecological responsibility. Resistance management should no longer be viewed as an optional practice but as a central component of agricultural planning. Governments, researchers, extension agencies, and farming communities must collaborate to promote sustainable crop protection systems. Technological innovation alone cannot solve resistance problems unless supported by informed decision making and practical field level implementation.

Conclusion

Pesticide resistance represents one of the most pressing challenges facing modern agriculture. Although pesticides continue to play an important role in crop protection, excessive and repetitive use has reduced their long term effectiveness. Resistance leads to economic losses, environmental concerns, and increased pressure on agricultural systems. Addressing this issue requires moving beyond chemical dependence toward integrated and science based approaches. Through Integrated Pest Management, improved farmer awareness, biological alternatives, and technological innovation, agriculture can continue to protect crops while preserving environmental sustainability. Sustainable resistance management is not simply about maintaining pesticide effectiveness, it is about securing the future of food production.

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