International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Green Alternatives to Conventional Synthetic Pesticides

*Dr. Rahul Arya, [1]Dr. Pooja Tomar, [2]Dr. Reetu Pundir, [3]Dr. Manoj Mittal , [4]Vivek

Department of Basic Science Shri Ram College, Muzaffarnagar (U.P), India

ABSTRACT :

This paper examines the toxicological effects of traditional synthetic pesticides on the environment and living things, including people, and looks into environmentally friendly, sustainable substitutes like biopesticides, compounds derived from plants, and solutions made possible by nanotechnology. The study highlights the pressing need for agriculture to transition to green chemistry-based methods in order to lower health and environmental hazards while preserving crop yields. The extensive use of traditional synthetic pesticides in agriculture and pest control has raised serious questions about their toxicity to the environment, non-target organisms, and people. These chemicals' high persistence, bioaccumulation potential, and correlations with both acute and chronic health conditions—such as endocrine disruption, neurotoxicity, and carcinogenicity—are revealed by toxicity profiling. Green alternatives like microbial agents, botanical extracts, biopesticides, and RNA-based pesticides are becoming more and more popular worldwide in response to these worries. These environmentally friendly alternatives' biodegradability, selectivity, and reduced residual toxicity provide promising pest control efficacy while reducing harmful effects on the environment and human health. Regulatory barriers, limited market availability, pest resistance, and cost-effectiveness at scale are still issues despite their potential. This review compares the toxicity profiles of synthetic and environmentally friendly pesticides, assesses the effectiveness and usefulness of substitutes, and emphasizes the necessity of multidisciplinary, integrated approaches. The shift to green pest management supports international environmental and public health objectives in addition to sustainable agricultural methods.

Key Words: Biopesticides, Pesticides, Toxicological impacts, Nanotechnology, Agriculture, Conventional Synthetic Pesticides, RNA, Eco-friendly, Health, Sustainable, Biodegradability

Introduction:

In order to guarantee high crop yields and provide protection against pests, weeds, and diseases, synthetic pesticides have become increasingly popular as a result of the world's agriculture industry's explosive growth. These traditional pesticides—which include pyrethroids, carbamates, organochlorines, and organophosphates—have been essential to contemporary farming methods. But their pervasive and frequently careless use has sparked grave worries about ecological imbalance, environmental contamination, and detrimental impacts on both human and animal health.

1. Toxicological The scientific evaluation of synthetic pesticides' detrimental effects on diverse biological systems is known as "profileing." This covers endocrine disruption, carcinogenicity, teratogenicity, acute and chronic toxicity, and ecotoxicity. Numerous pesticides are hazardous to non-target organisms like pollinators, aquatic species, and soil microbes, and they bioaccumulate in the food chain. Long-term human exposure has also been connected to immunological, neurological, and reproductive problems.
Green alternatives, or environmentally friendly pest control techniques that adhere to the concepts of green chemistry, are being developed and adopted at an accelerating rate as awareness of these problems rises. These include herbal extracts like neem and pyrethrin; biopesticides, which are made from natural sources like bacteria, fungi, and plants; and integrated pest management (IPM) techniques, which combine biological, cultural, and mechanical methods to reduce the use of pesticides.

In addition to investigating workable green alternatives that can lessen ecological harm while preserving agricultural productivity, this project seeks to present a thorough toxicity profile of synthetic pesticides that are frequently used. The study emphasizes the urgent need for safer pest management practices to ensure food security, environmental sustainability, and public health protection.

2. Conventional Synthetic Pesticides

Chemically produced substances called synthetic pesticides are intended to eradicate or deter pests that endanger property, public health, and crops. They are divided into groups according to the kind of pest they target and their chemical makeup. The most commonly utilized groups are pyrethroids, carbamates, organochlorines, and organophosphates. Although they have made significant contributions to crop productivity and pest control, they are also linked to a number of toxicological and environmental issues.

2.1 Major Classes and Examples

Class	*Examples*	*Mode of Action*
Organochlorines	DDT, Lindane	Disrupt sodium ion channels in neurons
Organophosphates	Malathion, Parathion	Inhibit acetylcholinesterase, causing neurotoxicity
Carbamates	Carbaryl, Aldicarb	Reversibly inhibit acetylcholinesterase
Pyrethroids	Permethrin, Cypermethrin	Prolong sodium channel activation in nerves

2.2 Environmental and Health Hazards

Both humans and animals can become acutely (short-term) and chronically (long-term) toxically affected by conventional pesticides. Exposure symptoms can include anything from cancer and neurotoxicity to skin irritation and respiratory problems. Pesticides frequently damage non-target species like pollinators, earthworms, and aquatic organisms, remain in soil and water, and build up in the food chain.

Toxicological Concerns*:*

- *Bioaccumulation and Biomagnification*: Persistent compounds like DDT accumulate in fatty tissues and magnify through the food chain.
- *Endocrine Disruption*: Some pesticides mimic hormones, interfering with reproductive and developmental processes (e.g., Atrazine).
- *Neurotoxicity*: Organophosphates and carbamates affect the nervous system, particularly in children (Bouchard et al., 2010).
- *Carcinogenicity*: Glyphosate and other compounds have been classified as probable human carcinogens (IARC, 2015).

2.3 Regulatory Response

Numerous nations have restricted or outright banned synthetic pesticides due to mounting evidence of their detrimental effects. When assessing the safety of pesticides, regulatory agencies like the Central Insecticides Board & Registration Committee (CIBRC) in India, the European Food Safety Authority (EFSA), and the U.S. Environmental Protection Agency (EPA) are essential.

3. Toxicity Profiling

Assessing the detrimental effects of chemicals, such as traditional synthetic pesticides, on biological systems and ecosystems is known as toxicity profiling. This covers their environmental persistence, food chain entry, and impacts on ecological and human health. Numerous synthetic pesticides have shown a variety of toxicological risks as a result of their extensive and frequent use; these risks vary based on the chemical structure, dosage, exposure method, and environmental circumstances.

3.1 Environmental Toxicity

By means of spraying, leaching, runoff, and volatilization, synthetic pesticides have the potential to contaminate soil, water, and air. Aquatic ecosystems are disturbed, beneficial microbial communities are destroyed, and soil fertility is decreased by these contaminants.
Soil contamination: Pesticides such as DDT and endosulfan can linger in the soil for years, changing the nutrient cycle and soil microbiota.
Water pollution: Surface and groundwater are contaminated by pesticide runoff, which impacts aquatic life and sources of drinking water.
Air pollution: Aerial spraying and volatile pesticides can cause drift, contaminating the surrounding environment and endangering human populations nearby.
Example: Chlorpyrifos, a widely used organophosphate, has been detected in soil and groundwater near agricultural zones and has been shown to persist longer than previously expected (Racke, 1993).

3.2 Human Health Impacts

Acute Toxicity:
Short-term exposure can result in skin irritation, headaches, nausea, dizziness, respiratory distress, and in extreme situations, death.
Because they come into direct contact with pesticides while they are being applied, farm workers and applicators are most at risk.
Chronic Toxicity: Prolonged exposure is associated with developmental defects, cancer, endocrine disruption, neurological disorders, and reproductive issues.
Inhibiting acetylcholinesterase, organophosphates impact the function of the brain and nervous system, particularly in children (Bouchard et al., 2010).
The IARC (2015) has categorized glyphosate as "probably carcinogenic to humans."
3.3 The processes of bioaccumulation and biomagnification
Numerous synthetic pesticides are lipophilic, meaning they build up in the fatty tissues of living things, particularly organochlorines like DDT and lindane. These substances gradually bioaccumulate in distinct organisms.
biomagnify their way up the food chain to dangerous levels in top predators (e.g., humans, birds of prey).
Result in reproductive failures, hormonal disruption, and weakened immunity.

Example: DDT's accumulation in bird species led to thinning of eggshells, causing major population declines in species like the bald eagle (Carson, 1962).

3.4 Effects on Non-Target Organisms

Pollinators (e.g., bees, butterflies):

1. Neonicotinoids and pyrethroids are especially harmful to *honeybees***,** affecting navigation, foraging behavior, and reproduction.
2. Colony Collapse Disorder (CCD) has been linked to pesticide exposure.

Aquatic life:

Pesticide runoff into rivers and lakes can cause *fish kills*, developmental abnormalities in amphibians, and reduction in aquatic biodiversity.

Beneficial insects and soil fauna:

Predatory insects, parasitoids, and decomposers such as earthworms are killed by broad-spectrum insecticides, reducing natural pest control and soil health.

Example: Imidacloprid has been shown to reduce the foraging activity and survival of bumblebees (Gill et al., 2012).

4. Legislation and Regulations

Pesticide use is strictly governed by national and international regulatory frameworks to minimize risks to human health and the environment. These *regulations address toxicity profiling, risk assessment, permissible exposure levels, environmental persistence, and safety measures* for pesticide production, distribution, application, and disposal. Despite these frameworks, enforcement gaps and variations in policy across regions often lead to misuse and overuse, particularly in developing countries.

4.1 Overview of National and International Pesticide Regulation

***International Agencies and Frameworks*:**

- *World Health Organization (WHO)*: Classifies pesticides based on acute toxicity (Classes Ia to U) and collaborates with countries to develop health-based exposure guidelines (WHO, 2020).
- *Food and Agriculture Organization (FAO)*: Publishes the *International Code of Conduct on Pesticide Management*, promoting responsible pesticide use and trade.
- *Stockholm Convention* (under UNEP): Aims to eliminate or restrict persistent organic pollutants (POPs), including DDT, aldrin, and endrin.
- *Rotterdam Convention*: Promotes shared responsibilities in the import/export of hazardous chemicals.
- *Codex Alimentarius Commission* (WHO/FAO): Sets international *Maximum Residue Limits (MRLs)* in food commodities.

***United States – Environmental Protection Agency (EPA)*:**

- Registers pesticides under the *Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)*.
- Conducts ecological and human risk assessments.
- Sets *tolerances (MRLs)* for pesticide residues in food under the *Food Quality Protection Act (FQPA)***.**

***India*:**

- *Central Insecticides Board & Registration Committee (CIBRC)* under the *Insecticides Act, 1968* regulates manufacture, import, sale, transport, and use of pesticides.
- Enforces quality control, label specifications, and approves pesticides for use in Indian agriculture.
- The upcoming *Pesticide Management Bill, 2020* aims to tighten regulations, improve transparency, and protect farmer interests.

4.2 Banned and Restricted Pesticides

Due to proven health and environmental risks, several synthetic pesticides have been *banned or restricted* across many countries.

Pesticide	*Status in India*	*Toxicity Concern*
DDT	Banned for agricultural use (2006); restricted for malaria control	Persistent, carcinogenic
Aldrin, Endrin	Banned	Persistent organic pollutants (POPs)
Carbofuran	Banned	Highly toxic to birds and humans
Chlorpyrifos	Banned in US (2021), under review in India	Neurotoxic, especially in children
Monocrotophos	Banned in many countries	Acute toxicity, linked to mass poisonings in India

In India, 99 pesticides have been banned to date (as per CIBRC, 2023). Several others are under regulatory scrutiny for their health risks.

4.3 Safety Standards and Permissible Exposure Limits

To prevent health hazards from pesticide residues, regulatory bodies establish *acceptable exposure levels***:**

Key Exposure Metrics:

a. *ADI (Acceptable Daily Intake)***:** The amount of a pesticide that can be consumed daily over a lifetime without adverse effects.
b. *NOAEL (No Observed Adverse Effect Level)*: The highest tested dose without toxic effect.
c. *MRL (Maximum Residue Limit)***:** The highest legal amount of pesticide residue allowed in or on food commodities.
d. *Reference Dose (RfD)***:** An estimate of daily exposure that is likely to be without harmful effects during a lifetime.

Examples of Regulatory Standards:

e. *WHO* sets MRLs in Codex Alimentarius for international trade.
f. *EPA (USA)* publishes detailed health benchmarks and sets RfDs for all registered pesticides.
g. *FSSAI (India)* uses Codex MRLs and national standards to ensure food safety.

Despite these frameworks, poor implementation, lack of awareness among farmers, and black-market sales of banned substances continue to undermine safety efforts in several developing countries.

5. Green Alternatives to Synthetic Pesticides

As the environmental and health hazards of synthetic pesticides become increasingly evident, the search for sustainable and eco-friendly alternatives has gained momentum. Green pest management strategies aim to control pests while minimizing adverse effects on human health, non-target organisms, and the environment. These approaches include *biopesticides***,** *cultural and mechanical practices***,** *integrated pest management (IPM)***,** and *innovative technologies* like *nanoformulations* **and** *RNA interference (RNAi)***.**

5.1 Biopesticides

Biopesticides are derived from natural sources such as *microorganisms***,** *plants***,** and *insect pheromones*. They are biodegradable, target-specific, and generally pose minimal risk to humans and the environment.

a) Microbial Pesticides

a. Contain active ingredients from bacteria, fungi, viruses, or protozoa.
b. Example: *Bacillus thuringiensis (Bt)* produces crystal proteins toxic to lepidopteran larvae.
c. Used in genetically modified Bt crops (e.g., Bt cotton, Bt corn).

b) Botanical Extracts

Derived from plants with natural pesticidal properties.

Examples:*Neem(Azadirachta indica)*–antifeedant, growth inhibitor, *Pyrethrin* from chrysanthemum - neurotoxin for insects, biodegradable- Typically safer for pollinators and humans.

c) Pheromones

Synthetic versions of insect sex or aggregation pheromones used for:

a. Mating disruption
b. Pest monitoring and mass trapping
c. Highly species-specific and non-toxic to non-target organisms.

5.2 Cultural and Mechanical Practices

These are preventive methods that modify the environment or practices to suppress pest populations.

a. *Crop Rotation*: Disrupts pest life cycles by alternating crops.
b. *Intercropping*: Diversifies plant types to confuse pests and attract natural enemies.
c. *Pest Traps*: Light traps, sticky traps, and pheromone traps for physical pest removal.
d. *Mulching and tillage*: Suppresses weed growth and pest habitats.

Such practices are *cost-effective*, *non-toxic*, and can significantly reduce pesticide dependence when used properly.

5.3 Integrated Pest Management (IPM)

IPM is a holistic, decision-making approach that combines biological, cultural, mechanical, and chemical tools to manage pests sustainably and economically.

Key IPM Principles:

a. Monitoring pest populations and setting action thresholds.
b. Encouraging *biological control* (e.g., predators like ladybugs, parasitoid wasps).
c. Minimal use of *least-toxic chemicals* only when needed.
d. Promotes *resistance management* and long-term sustainability.

IPM is recognized by *FAO* and *WHO* as a preferred strategy for sustainable agriculture.

5.4 Nanoformulations

Nanopesticides use nanotechnology to improve pesticide delivery, reduce doses, and minimize environmental contamination. Nanocarriers such as *nanoemulsions*, *nanocapsules*, and *nanogels* allow controlled release. **It** *Reduced volatility and leaching* decrease non-target exposure.
Example: Neem oil nanoemulsion for increased stability and efficacy.
Challenges: Regulatory approval, cost, and potential unknown long-term effects.

5.5 RNA Interference (RNAi) and Emerging Technologies

RNAi-based pesticides are gene-specific tools that silence critical genes in pest species by introducing double-stranded RNA (dsRNA).
Highly *target-specific*, minimizing effects on non-target organisms.
Example: Corn rootworm control using RNAi technology (approved by EPA, 2017).
Other promising innovations:
RISPR gene-editing for pest-resistant crops.
Artificial intelligence (AI) for pest prediction and smart spraying.
Drones and robotics for precision pest detection and management.

Comparative Assessment
(Toxicity Profiling and Green Alternatives to Conventional Synthetic Pesticides)
1. Efficacy of Green Alternatives vs. Synthetic Pesticides
Synthetic pesticides are often highly effective in the short term due to their rapid action and broad-spectrum activity. However, their overuse can lead to pesticide resistance, resurgence of pests, and destruction of beneficial organisms. In contrast, green alternatives such as biopesticides and integrated pest management (IPM) provide targeted pest control with reduced environmental footprint. While their efficacy may initially appear lower, many green alternatives offer sustained control when used as part of a holistic pest management strategy.

Example:

- Neem-based formulations have shown significant pest control in crops like cotton, rice, and vegetables, often with reduced development of resistance compared to synthetic counterparts (Isman, 2006).
- Microbial pesticides such as *Bacillus thuringiensis* (Bt) are highly specific and effective against caterpillar pests, with minimal effects on non-target organisms.

2. Toxicity Profile Comparison

Parameter	**Synthetic Pesticides**	**Green Alternatives**
Human Toxicity	High (neurotoxic, carcinogenic)	Low to negligible
Environmental Persistence	High (residues in soil, water)	Low (biodegradable)
Bioaccumulation	Common	Rare
Non-target Impact	Significant (pollinators, birds, aquatic life)	Minimal
Resistance Development	Frequent	Rare (with IPM use)

3. Cost-effectiveness and Scalability

a. **Synthetic pesticides** are often cheaper and readily available due to large-scale manufacturing and government subsidies. However, the **externalized costs** (e.g., health care, environmental remediation) make them less sustainable in the long term.
b. **Green alternatives**, especially microbial and botanical pesticides, may have higher upfront costs and shorter shelf life, but offer long-term sustainability and safety. With government incentives and training, their adoption is increasing.
c. **Scalability** is improving through nanoformulations and improved shelf-stable biopesticide products.

4. Case Studies of Successful Green Pest Control
i. Sikkim, India (Organic State Initiative):

a. Fully banned chemical pesticides and adopted organic and biological pest management.
b. Resulted in improved soil health, biodiversity, and crop sustainability (FAO, 2018).

ii. Bt Cotton in India and the USA:

a. *Bacillus thuringiensis* integrated into cotton crops reduced the need for synthetic insecticides.
b. Lower pest-related losses and improved yield (Shelton et al., 2002).

iii. IPM in Rice (Vietnam and Philippines):
Use of pest-resistant varieties, biological control agents, and farmer education reduced pesticide usage by over 50% without yield loss (Matteson, 2000).

7. Challenges and Limitations

Despite the growing interest in green alternatives to synthetic pesticides, several **challenges and limitations** hinder their widespread adoption and effective implementation. These challenges span biological, economic, regulatory, and educational domains, posing barriers to sustainable pest management.

1. Resistance Development in Pests
Although one of the aims of green pest control is to reduce resistance, even **biopesticides** are not immune. Continuous use of specific microbial agents or botanicals may lead to adaptive responses in pest populations.
Example: Pests like *Helicoverpa armigera* have shown reduced susceptibility to **Bacillus thuringiensis (Bt)** toxins in areas with prolonged Bt crop use.
Mechanism: Pests may develop enzymatic degradation, altered target sites, or behavioral avoidance over time.

2. Market Availability and Awareness
Many farmers, especially in developing regions, are unaware of or have limited access to **green alternatives** such as biopesticides or integrated pest management (IPM) tools.
Reasons:

a. Lack of extension services and training
b. Limited shelf life and storage requirements of some biopesticides
c. Inadequate distribution channels

Result: Farmers often rely on easily available synthetic chemicals despite known toxicity risks.
3. Regulatory Gaps in Biopesticide Use
The **regulatory frameworks** for green pesticides are still evolving and often lag behind those of synthetic pesticides.

Challenges:

a. Lack of harmonized international standards
b. High registration costs and lengthy approval timelines for new biopesticides
c. Inadequate risk assessment protocols specific to microbial and botanical pesticides

Example: While the **EPA (USA)** has relatively streamlined biopesticide approval, many countries lack separate registration pathways, delaying market entry.
4. Variability in Efficacy
Unlike synthetic pesticides, biopesticides and botanicals often have slower action, shorter persistence, and can be more sensitive to environmental conditions like UV light and humidity.
Example: Neem-based pesticides degrade rapidly in sunlight, reducing their field effectiveness unless applied repeatedly.
Consequence: Farmers may find them less reliable for immediate pest outbreaks.

5. Economic and Infrastructural Constraints
Developing countries often face:

a. Limited investment in green technology R&D
b. Poor lab-to-field transfer
c. Lack of cold chain or storage facilities for microbial agents

8. Future Directions

As the global agriculture sector strives for sustainability, the transition from conventional synthetic pesticides to green alternatives requires robust strategies informed by science, policy, and practice. Future directions in this field highlight key research gaps, policy interventions, and interdisciplinary collaboration needed to make pest control both effective and environmentally responsible.

8.1 Research Needs in Toxicity Testing of Alternatives

Although green alternatives such as biopesticides, botanical extracts, and RNAi-based products are generally considered safer, comprehensive toxicity profiles are often lacking. It is critical to assess:

a. Ecotoxicity, including impacts on soil microbiota and aquatic ecosystems.
b. Chronic exposure risks for humans and animals.
c. Standardized toxicity metrics (e.g., LD_{50}, NOAEL) for comparing green and synthetic products.

8.2 Policy Recommendations

To ensure safe and effective adoption of green pesticides, policies must:

a. Streamline regulatory frameworks for faster approval of biopesticides.
b. Promote incentives for farmers adopting sustainable pest control practices.
c. Mandate toxicity and efficacy testing even for natural-origin products.
d. Strengthen post-marketing surveillance to monitor real-world impacts.

8.3 Need for Interdisciplinary Approaches in Green Chemistry and Agriculture

Solving the complex challenge of pest management sustainability requires collaboration across disciplines, such as:
Green Chemistry: Designing pest control molecules that degrade quickly and have minimal off-target toxicity.
Agricultural Sciences: Tailoring biocontrol methods for specific crops, climates, and pest profiles.
Environmental Toxicology: Evaluating long-term ecological impacts of green alternatives.
Data Science: Modeling pest dynamics, resistance patterns, and environmental dispersion.
Interdisciplinary research can also foster innovations such as:
Smart pesticide delivery using nanotechnology.
CRISPR and RNAi technologies for targeted gene silencing in pests.

9. Methodology (Experimental Approach)

To comprehensively assess the toxicity of conventional synthetic pesticides and explore green alternatives, a *multi-pronged methodology* is adopted. It includes a literature-based analysis, experimental bioassays (if feasible), and optional field data collection on awareness and usage of biopesticides among farmers.

9.1 Literature Review of Pesticide Toxicity Reports

A thorough literature review was conducted using peer-reviewed journals, regulatory databases (EPA, WHO, FAO), and government reports. The review focused on:
Toxicity indicators such as:

a. *LD_{50} (Lethal Dose 50%)*: Dose required to kill 50% of the test population.
b. *NOAEL (No Observed Adverse Effect Level)*: Maximum dose showing no observable harmful effects.
c. *LOAEL (Lowest Observed Adverse Effect Level)*
d. *ADI (Acceptable Daily Intake)*
e. *MRLs (Maximum Residue Limits)*

Toxicity data were collected for a representative sample of pesticides (e.g., DDT, chlorpyrifos, carbaryl, glyphosate) and compared with data for biopesticides (e.g., neem extract, *Bacillus thuringiensis*).

9.2 Comparative Analysis of Toxicity Data

Collected toxicity values were tabulated and analyzed to compare synthetic and green alternatives: *Quantitative comparison* of LD_{50} and NOAEL values between synthetic pesticides and biopesticides.
Graphical representation of toxicity ranges (e.g., mg/kg body weight) for different organisms (rats, bees, fish).

Risk categorization (WHO hazard classes Ia–U).
Example Comparison:

Pesticide	LD_{50} (oral, rat, mg/kg)	WHO Class	Bioaccumulative
DDT	113	II	Yes
Chlorpyrifos	135	II	Moderate
Neem Extract (Azadirachtin)	>2,000	U (unlikely)	No
Bt Toxin	>5,000	U	No

10. Conclusion:

10.1 Summary of Findings:

The increasing reliance on conventional synthetic pesticides has raised major concerns about human health risks, environmental degradation, and non-target toxicity. Toxicity profiling reveals that many of these compounds persist in the environment, bioaccumulate in food chains, and are linked to a range of chronic and acute health effects. In contrast, green alternatives—including biopesticides, botanical extracts, microbial agents, and RNA-based pesticides—offer targeted efficacy, lower toxicity, and biodegradability.

a. Green pesticides demonstrate lower LD_{50} values for non-target organisms.
b. Case studies (e.g., neem-based biopesticides in cotton) show comparable efficacy to synthetic ones.
c. Despite challenges, the cost-effectiveness and scalability of some eco-friendly options are improving with research and innovation.

10.2 Advocacy for Green Transition in Pest Control

Given the toxicological and environmental burden of synthetic pesticides, there is an urgent need for a global transition toward greener pest management strategies. Policymakers, researchers, and the agro-industry must collaboratively:

a. Incentivize farmers to adopt eco-friendly pest control.
b. Streamline regulatory approvals for biopesticides and green products.
c. Promote education and awareness campaigns for stakeholders.
d. Support public–private partnerships for innovation in green agrochemicals.

10.3 Environmental and Health Benefits of Adopting Eco-Friendly Alternatives

a. Transitioning to green alternatives promises multiple co-benefits:
b. Reduced soil and water contamination, preserving ecosystem health.
c. Minimized residue in food, improving consumer safety.
d. Preservation of beneficial insects (e.g., bees, pollinators, soil organisms).
e. Mitigation of resistance development in pests.

Such practices also align with the UN Sustainable Development Goals (SDGs), particularly those focused on health (SDG 3), clean water (SDG 6), and responsible consumption (SDG 12).

REFERENCES:

1. Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. *Interdisciplinary Toxicology*, *2*(1), 1–12. https://doi.org/10.2478/v10102-009-0001-7
2. EPA (U.S. Environmental Protection Agency). (2023). *Pesticide Chemical Search*. https://www.epa.gov
3. Bouchard, M. F., Chevrier, J., Harley, K. G., et al. (2010). Prenatal exposure to organophosphate pesticides and IQ in 7-year-old children. *Environmental Health Perspectives*, *119*(8), 1189–1195. https://doi.org/10.1289/ehp.1003185
4. Carson, R. (1962). *Silent Spring*. Boston: Houghton Mifflin.
5. CIBRC (2023). *List of Banned Pesticides in India*. Ministry of Agriculture, India. https://ppqs.gov.in/divisions/cib-rc
6. Codex Alimentarius Commission (2023). *Pesticide Residues in Food and Feed*. https://www.fao.org/fao-who-codexalimentarius
7. Bhanti, M., & Taneja, A. (2007). Contamination of vegetables with pesticide residues in Lucknow, India. *Ecotoxicology and Environmental Safety*, *65*(3), 402–409.
8. Damalas & Eleftherohorinos (2011) highlight that synthetic pesticides contribute heavily to environmental and human health hazards, while biopesticides exhibit lower toxicity and eco-friendliness
9. Isman, M. B. (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*, *51*, 45–66. https://doi.org/10.1146/annurev.ento.51.110104.151146
10. Chandler, D. et al. (2011). The development, regulation, and use of biopesticides for integrated pest management. *Philosophical Transactions of the Royal Society B*, *366*, 1987–1998. https://doi.org/10.1098/rstb.2010.0390
11. FAO (2022). *International Code of Conduct on Pesticide Management*. https://www.fao.org/pesticide-management
12. Kookana, R. S. et al. (2014). Nanopesticides: Guiding principles for regulatory evaluation of environmental risks. *Journal of Agricultural and Food Chemistry*, *62*(19), 4227–4240.
13. Damalas, C.A. & Eleftherohorinos, I.G. (2011). *Pesticide Exposure, Safety Issues, and Risk Assessment Indicators.* International Journal of Environmental Research and Public Health, 8(5), 1402–1419.
14. Isman, M.B. (2006). *Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world.* Annual Review of Entomology, 51, 45–66.
15. Kumar, S., et al. (2021). *Biopesticides: Current status and prospects.* Journal of Agriculture and Food Research, 3, 100035.
16. FAO (2018). *Sikkim: A 100% Organic State.* www.fao.org
17. Shelton, A.M., et al. (2002). *Economic, ecological, food safety, and social consequences of the deployment of Bt transgenic plants.* Annual Review of Entomology, 47, 845–881.
18. Matteson, P.C. (2000). *Insect pest management in tropical Asian rice.* Annual Review of Entomology, 45, 549–574.
19. Tabashnik, B. E., Brévault, T., & Carrière, Y. (2013). Insect resistance to Bt crops: lessons from the first billion acres. *Nature Biotechnology*, **31**(6), 510–521. https://doi.org/10.1038/nbt.2597
20. Chandler, D., et al. (2011). *The development, regulation and use of biopesticides for integrated pest management*. Philosophical Transactions of the Royal Society B, 366(1573), 1987–1998.
21. Cressey, D. (2013). *Biopesticides boom*. Nature, 501(7467), 471–472

22. Isman, M. B. (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*, **51**, 45–66

23. FAO & WHO. (2020). *International Code of Conduct on Pesticide Management – Guidelines on Biopesticides Registration*.

24. EPA (2021). *Biopesticide Registration and Regulation*. https://www.epa.gov/ingredients-used-pesticide-products/biopesticide-active-ingredients

25. Anastas, P. T., & Warner, J. C. (1998). *Green Chemistry: Theory and Practice*. Oxford University Press.

26. Romeis, J., et al. (2020). *RNAi technology in crop protection: Potential and challenges*. Nature Plants, 6(9), 842–852.

27. WHO (2020). *The WHO Recommended Classification of Pesticides by Hazard*. https://www.who.int/publications/i/item/9789240005662

28. EPA (2023). *Integrated Risk Information System (IRIS)*. https://www.epa.gov/iris

29. PPDB – Pesticide Properties DataBase (University of Hertfordshire). https://sitem.herts.ac.uk/aeru/ppdb/en/

30. Isman, M. B. (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*, *51*, 45–66. https://doi.org/10.1146/annurev.ento.51.110104.151146

31. Ghosh, A., Chowdhury, N., & Chandra, G. (2012). Plant extracts as potential mosquito larvicides. *Indian Journal of Medical Research*, *135*(5), 581–598.

32. FAO (2022). *Pesticide Residues in Food and Feed*. Codex Alimentarius. https://www.fao.org/fao-who-codexalimentarius

33. Cressey, D. (2013). *Biopesticides boom*. Nature, 501(7467), 471–472.

34. WHO. (2021). *Pesticide residues in food*. https://www.who.int/news-room/fact-sheets/detail/pesticide-residues-in-food

35. Isman, M. B. (2006). *Botanical insecticides, deterrents, and repellents in modern agriculture and increasingly regulated world*. Annu. Rev. Entomol. 51, 45–66.

36. EPA (2021). *Toxicity and Environmental Profiles of Pesticides*. https://www.epa.gov

37. Pretty, J., et al. (2018). *Sustainable intensification of agriculture: Greening the world's food economy*. International Journal of Agricultural Sustainability, 16(2), 101–117.