



IntechOpen

IntechOpen Series
Agricultural Sciences, Volume 41

New Horizons in Insecticides Research

Edited by Farzana Khan Perveen



New Horizons in Insecticides Research

Edited by Farzana Khan Perveen

Published in London, United Kingdom

New Horizons in Insecticides Research
<http://dx.doi.org/10.5772/intechopen.1011259>
Edited by Farzana Khan Perveen

Contributors

Arbaz Khan, Chuanxi Yang, Farzana Khan Perveen, Hajra Bari, Ishfa Tahani, Jofy Francis, Kaipeng Sun, Mingfang Zhang, Muhammad Yaseen, Naser A. Anjum, Pavithra Deenadayalan, Pushpa Rani Vedham, Rizah Akbar, Sarfraz Ali Shad, Sehrish Zafar, Tehreem Fatima, Xiaoning Wang, Yiyong Xu, Yongkun Wu, Ziheng Wan

© The Editor(s) and the Author(s) 2026

The rights of the editor(s) and the author(s) have been asserted in accordance with the Copyright, Designs and Patents Act 1988. All rights to the book as a whole are reserved by INTECHOPEN LIMITED. The book as a whole (compilation) cannot be reproduced, distributed or used for commercial or non-commercial purposes without INTECHOPEN LIMITED's written permission. Enquiries concerning the use of the book should be directed to INTECHOPEN LIMITED rights and permissions department (permissions@intechopen.com).

Violations are liable to prosecution under the governing Copyright Law.



Individual chapters of this publication are distributed under the terms of the Creative Commons Attribution 4.0 License which permits commercial use, distribution and reproduction of the individual chapters, provided the original author(s) and source publication are appropriately acknowledged. If so indicated, certain images may not be included under the Creative Commons license. In such cases users will need to obtain permission from the license holder to reproduce the material. More details and guidelines concerning content reuse and adaptation can be found at <http://www.intechopen.com/copyright-policy.html>.

Notice

Statements and opinions expressed in the chapters are those of the individual contributors and not necessarily those of the editors or publisher. No responsibility is accepted for the accuracy of information contained in the published chapters. The publisher assumes no responsibility for any damage or injury to persons or property arising out of the use of any materials, instructions, methods or ideas contained in the book.

First published in London, United Kingdom, 2026 by IntechOpen

IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 167-169 Great Portland Street, London, W1W 5PF, United Kingdom

For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

New Horizons in Insecticides Research

Edited by Farzana Khan Perveen

p. cm.

This title is part of the Agricultural Sciences Book Series, Volume 41

Topic: Agronomy and Horticulture

Series Editor: W. James Grichar

Topic Editors: Murat Helvacı and Olga Panfilova

Print ISBN 978-1-80631-265-8

Online ISBN 978-1-80631-264-1

eBook (PDF) ISBN 978-1-80631-266-5

ISSN 3029-052X

If disposing of this product, please recycle the paper responsibly.

IntechOpen Book Series

Agricultural Sciences

Volume 41

Aims and Scope of the Series

The importance of agriculture cannot be overstated. It helps sustain life, as it gives us the food we need to survive and provides opportunities for economic well-being. Agriculture helps people prosper around the world and combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies. This series includes two main topics: Agronomy and Horticulture, and Animal Farming. This series will help readers better understand the intricacies of production agriculture and provide the new knowledge that is required to be successful. The success of a farmer in modern agriculture requires knowledge of events happening locally as well as globally that impact input decisions and ultimately determine net profit.

Meet the Series Editor



W. James Grichar has been employed with Texas A&M AgriLife Research for over 45 years with an emphasis on research in agronomy, plant pathology, and weed science. He obtained his BS from Texas A&M in 1972 and his Masters of Plant Protection in 1975. He has published 195 journal articles, over 330 research reports and briefs, 11 book chapters, and over 300 abstracts of profession meetings. He also directs research in many crops including corn, grain sorghum, peanuts, and sesame. He has held various positions in different professional societies including the American Peanut Research and Education Society, Southern Weed Science Society, and Texas Plant Protection Conference in addition to being Associate Editor for Peanut Science and Weed Technology. Significant accomplishments have included spearheading efforts to determine the optimum planting time for soybean production along the upper Texas Gulf Coast. These efforts have shown growers that soybean yields can be improved by 10 to 20% by following a late March to early April plant date. He also has been instrumental in developing a herbicide program for peanut production in the south Texas growing region. Through the development and use of herbicides that are effective against major weed problems in the south Texas region, peanut yields have increased by 25 to 30%.

Meet the Volume Editor



Farzana Khan Perveen (FLS; Gold-Medallist) earned a BSc(Hons) and MSc from the University of Karachi, an MAS from Nagoya University, Japan, and a Ph.D. from the University of Karachi, which included research and coursework from Nagoya University. She is the Founder and Chairperson of the Department of Zoology (DOZ) and the former Controller of Examinations at Shaheed Benazir Bhutto University (SBBU). She is also the Founder and a former Chairperson of the Department of Zoology at Hazara University and Kohat University of Science & Technology. Currently, she is working as a Senior Scientist in Parasitology at the Faculty of Pharmacy and Medicine, University of Reims Champagne-Ardenne, in Reims, France. Her research interests are Entomology, Toxicology, Forensic Entomology, and Agriculture. She is the author of 150 high-impact research papers, 135 abstracts, 40 authored books, 15 chapters, and 11 edited books. She has supervised 4 BS, 50 MSc, 40 MPhil, and 1 Ph.D. student. She has organized and participated in numerous international and national conferences and has received multiple awards and fellowships. She is a member of research societies, editorial boards of journals, and the World Commission on Protected Areas of the International Union for Conservation of Nature.

Contents

Preface	XIII
Chapter 1	1
Introductory Chapter: Horizon Pesticides <i>by Farzana Khan Perveen</i>	
Chapter 2	5
Biodegradable, Green and Nanotechnology-Enabled Insecticides: Green Chemistry, Applications and Advances <i>by Pavithra Deenadayalan, Pushpa Rani Vedham and Jofy Francis</i>	
Chapter 3	27
Botanical Insecticides: Major Sources, and Chemical and Mechanistic Insights <i>by Rizah Akbar, Hajra Bari, Tehreem Fatima, Ishfa Tahani and Naser A. Anjum</i>	
Chapter 4	41
Perspective Chapter: Role of Insecticides in Biological Control Agents and Their Impacts <i>by Arbaz Khan, Muhammad Yaseen, Sehrish Zafar and Sarfraz Ali Shad</i>	
Chapter 5	59
Environmental Effects and Risk Control of Neonicotinoid Insecticides <i>by Xiaoning Wang, Chuanxi Yang, Yongkun Wu, Mingfang Zhang, Kaipeng Sun, Yiyong Xu and Ziheng Wan</i>	

Preface

This book consists of 5 chapters. The 1st chapter *Introductory Chapter: Horizon Pesticides* is written by Farzana Khan Perveen from the University of Reims Champagne-Ardenne, France. This chapter explores the current landscape of insecticides, the sophisticated resistance mechanisms that threaten their effectiveness, and the revolutionary “new horizons,” ranging from novel synthetic modes of action to bio-inspired nucleic acid technologies, that promise to redefine integrated pest management (IPM) in the 21st century. A few chemical classes dominate the modern insecticide market, each targeting a specific molecular structure in the insect’s nervous or muscular system. Neonicotinoids, acting as agonists of nicotinic acetylcholine receptors, are among the most widely used insecticides worldwide due to their systemic activity and broad spectrum of action. However, their high toxicity to bees and other beneficial insects has led to strict regulatory restrictions and their gradual withdrawal from the market in many regions, creating an urgent need for alternatives. Other important classes include pyrethroids (sodium channel modulators), diamides (ryanodine receptor activators), and spinosynes (allosteric modulators of nicotinic acetylcholine receptors). Insecticide resistance is a constant arms race, accelerated by the intensive use of chemicals. The main mechanisms—target site insensitivity, increased metal detoxification, and reduced cuticular penetration—are well documented. However, recent research has uncovered even more sophisticated resistance strategies.

The 2nd chapter, *Biodegradable, Green and Nanotechnology-Enabled Insecticides: Green Chemistry, Applications and Advances*, is written by Pavithra Deenadayalan et al. They critically examine the convergence of three core pillars: the phytosynthesis of metal nanoparticles, the valorization of agricultural waste (such as lignin and chitosan) into nanocarriers, and the engineering of solvent-free formulations. Beyond material sustainability, it focuses on “smart” functionality, specifically stimulus-responsive mechanisms, where release is triggered exclusively by pest-specific cues, such as alkaline gut pH or esterase activity, thereby minimizing non-target toxicity. Furthermore, the text addresses the environmental fate of these materials through the “Safe-by-Design” (SbD) framework, decoupling carrier degradation from active ingredient release to protect the soil microbiome. Finally, they analyze the “lab-to-field” gap, evaluating regulatory hurdles and the economic “dosage offset” required to make green nanotechnology commercially viable. The chapter concludes that integrating AI-driven polymer design with green chemistry offers a regenerative path forward, transforming pesticides from environmental pollutants into precise, nature-inspired agrotherapeutics (**Figure 1**).

The 3rd chapter, *Botanical Insecticides: Major Sources, and Chemical and Mechanistic Insights*, is written by Rizah Akbar et al. Taking into account recent literature, this chapter aims to: provide an overview of important insect pests and their impacts on crop health and productivity; highlight, with examples, the sources and chemical nature of major botanical insecticides (such as azadirachtin, pyrethrum, rotenone,

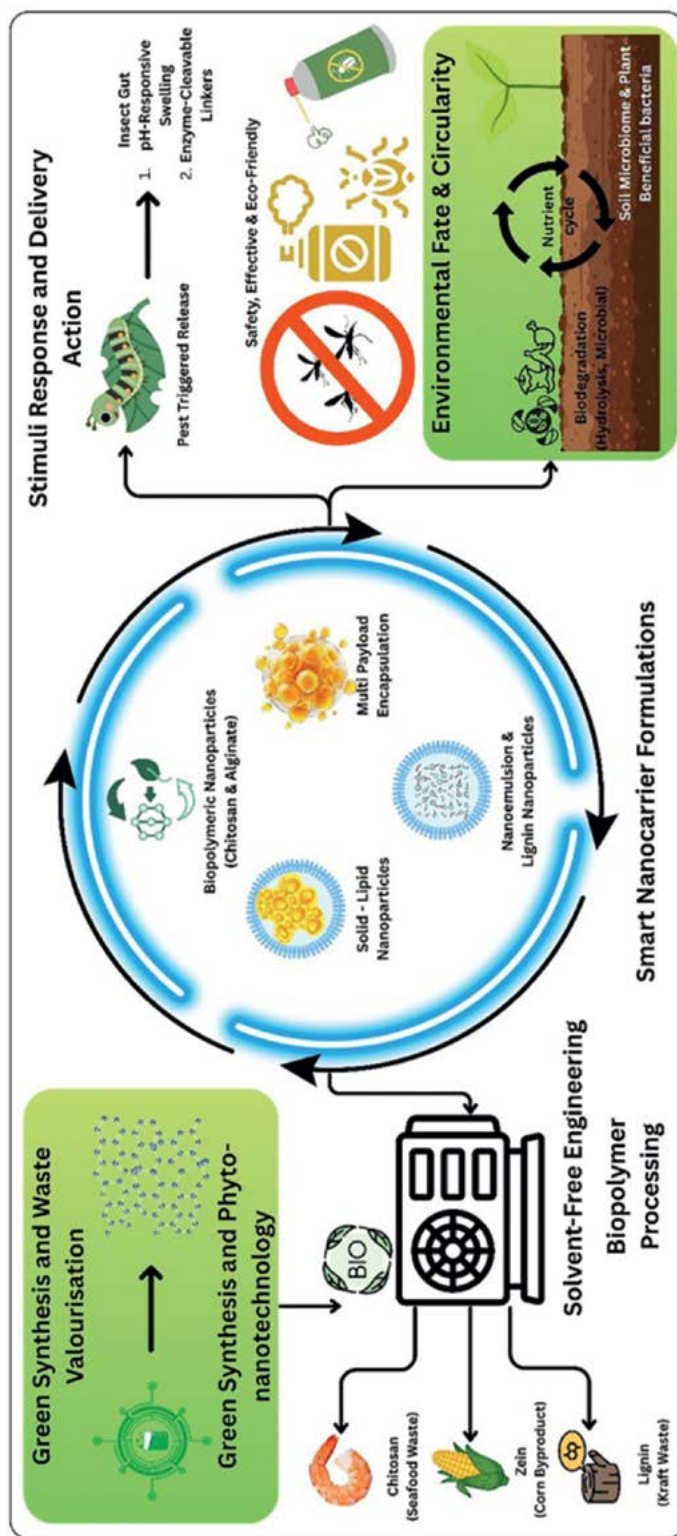


Figure 1. Schematic illustration of the “nano-green nexus”, depicting the conversion of agricultural waste into smart, stimuli-responsive nanocarriers that ensure pest-specific targeting and eco-friendly soil biodegradation.

allicin, and lemongrass essential oils); discuss important mechanistic insights (working principles) underlying botanical insecticides; and enlighten readers on the major challenges and future directions in this field. In particular, pests, weeds, and diseases pose a significant challenge to agriculture, causing an estimated 20-40% loss of global crop yields annually. These threats impact food security, increase production costs, and have environmental consequences through the use of control measures.

The 4th chapter, *Perspective Chapter: Role of Insecticides in Biological Control Agents and Their Impacts*, is written by Arbaz Khan et al. This chapter highlights the harmful effects of pesticides on natural and artificial biological control agents, exacerbating pest resistance and resurgence, challenging sustainable pest management. To mitigate these issues, this article emphasizes the need for selective pesticide use, the integration of biological resistance into control agents, and advanced studies on the effects of pesticides at the molecular and behavioral levels. Future directions advocate for innovative strategies to balance agricultural productivity with environmental and public health conservation. The three main categories of pesticides for the public are based on utility, entry into target species, and entity. Furthermore, the World Health Organization (WHO) classified them into four main groups: a) considerably harmful, b) moderately dangerous, c) greatly hazardous, and d) extremely hazardous (**Table 1**).

The 5th chapter, *Environmental Effects and Risk Control of Neonicotinoid Insecticides*, is written by Xiaoning Wang et al. It reported that NEOs are primarily emitted through industrial wastewater discharge, agricultural runoff, and sewage treatment plant effluents, and are frequently detected in water, soil, air, and biological matrices (human urine, tea, milk, and wildlife). Human exposure occurs mainly via dietary intake, with children and neonates showing higher vulnerability due to maternal-fetal transfer and immature metabolic systems. Ecologically, NEOs pose significant risks to non-target organisms, including birds, bees, and aquatic invertebrates, affecting their health, behavior, reproduction, and survival. Risk control strategies for NEOs include physicochemical technologies (adsorption, photocatalysis,

Pesticide type	Target organism	Mode of action	Human health risk	Environmental impact
Carbamates	Insects	Inhibit the acetylcholinesterase enzyme	Neurotoxicity	Harmful to non-target organisms
Organochlorines	Insects	Disrupt nerve transmission	Persistent in the body, causing cancer	Long-lasting in soil/water, banned
Pyrethroid	Insects	Damage to sodium channels in nerve cells	Low to moderate neurotoxic risk	Toxic to aquatic life
Neonicotinoids	Insects	Bind to nicotinic acetylcholine receptors	Behavioral change in humans/Animals	Lethal to bees and pollinators
Organophosphate	Insects	Overstimulates the nervous system	Linked to Parkinson's and cancer	Highly toxic contaminants in water

Table 1.
Comparative toxicity of major pesticide types.

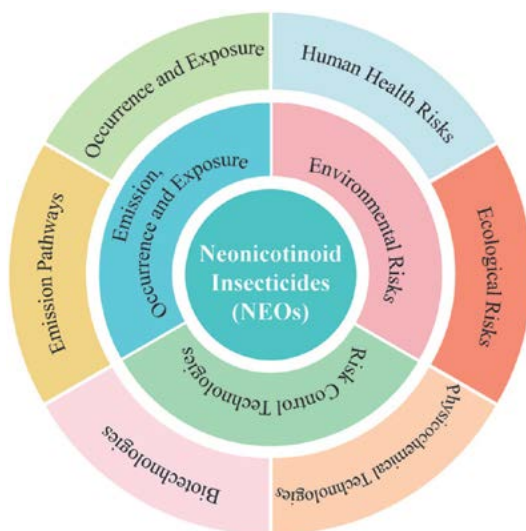


Figure 2.
Overview of environmental effects and risk control of neos.

Fenton-like processes) and biotechnologies (microbial degradation, phytoremediation), each with unique advantages and limitations. Key challenges remain the low detectability of transformation products, their potential toxicity, and the need for synergistic control strategies. This chapter provides a comprehensive overview of the environmental effects and the prevention and control of environmental risks posed by emerging contaminants, NEOs. Additionally, the complexity of NEOs' transformation products, some of which are more toxic than the parent compounds, poses new hurdles for risk assessment and control (**Figure 2**).

This book provides a comprehensive overview of new horizons in insecticide research, focusing on the key evidence for their various advantages. It is a useful resource for scientists, researchers, naturalists, conservationists, agriculturalists, biologists, professors, teachers, students, and anyone interested in insecticide research. The editor is grateful to all authors for their contributions. Special thanks go to all members of IntechOpen's publishing team and to the publishing process manager, Miss Laura Divic. The experiments described in this book comply with the current laws of the country in which they were performed.

Farzana Khan Perveen
Life Sciences, Natural Sciences, and Biotechnology,
Faculty of Pharmacy and Medicine,
University of Reims Champagne-Ardenne,
Reims, France

Chapter 1

Introductory Chapter: Horizon Pesticides

Farzana Khan Perveen

1. Introduction

A pesticide is a substance used to control organisms considered harmful. It is a generic term that encompasses insecticides, fungicides, molluscicides, herbicides, and antiparasitics used for their biocidal properties. Some are produced artificially by the chemical industry. Pesticides target insect pests, fungi, weeds, and parasitic worms [1].

This chapter explores the current landscape of insecticides, the sophisticated resistance mechanisms that threaten their effectiveness, and the revolutionary “new horizons,” ranging from novel synthetic modes of action to bio-inspired nucleic acid technologies that promise to redefine integrated pest management (IPM) in the twenty-first century. Pages are dedicated to Shenzhen Horizon Industry and Horizon Chem (a list of manufacturers of Horizon brand pesticides) [1].

The modern insecticide market is dominated by a few chemical classes, each targeting a specific molecular structure in the insect’s nervous or muscular system. Neonicotinoids, acting as agonists of nicotinic acetylcholine receptors, have become the most widely used insecticides in the world due to their systemic activity and broad spectrum of action. However, their high toxicity to bees and other beneficial insects has led to strict regulatory restrictions and their gradual withdrawal from the market in many regions, creating an urgent need for alternatives. Other important classes include pyrethroids (sodium channel modulators), diamides (ryanodine receptor activators), and spinosynes (allosteric modulators of nicotinic acetylcholine receptors).

Insecticide resistance is a constant arms race, accelerated by the intensive use of chemicals. The main mechanisms – target site insensitivity, increased metabolic detoxification, and reduced cuticular penetration – are well documented. However, recent research has uncovered even more sophisticated resistance strategies [2].

2. Sequestration resistance: A major discovery

Insects overexpress certain chemosensory proteins (CSPs) or odorant-binding proteins (OBPs) that physically bind to insecticide molecules and sequester them, preventing them from reaching their physiological target. For example, the SAP2 protein in the *Anopheles gambiae* is selectively bound to pyrethroids and confers

resistance to them. Similarly, in the brown rice leafhopper, *Nilaparvata lugens*, the overexpression of an OBP is linked to resistance to neonicotinoids such as nitenpyram [3].

3. New horizons for insecticide innovation

The next generation of insecticides is based on the principles of selectivity, environmental responsibility, and innovative biochemistry. These innovations fall into two main categories: new synthetic chemistries and biorational approaches. After 12 years of research and more than 3,200 trials, Syngenta is preparing to launch a new plinazoline-based insecticide in 2026 (marketed under the names Vertento® and Opello®). This compound represents the first insecticide with a novel mode of action in over a decade. Non-systemic and with residual surface action, it works by contact and ingestion, rapidly disrupting the pest's nervous system and causing paralysis. Its resistance to ultraviolet (UV) radiation and rain ensures long-lasting protection against various piercing-sucking and chewing insects, including bed bugs, brown marmorated stink bugs, and mites. The arrival of this new synthetic mode of action is essential to break resistance cycles and provide farmers with new, effective tools [4].

4. Integrated solutions and biorational alternatives

Ongoing field research continues to identify effective and safer alternatives to existing chemical formulations. For example, trials conducted in several states have demonstrated that insecticides such as cyantraniliprole (a diamide) and spinosad can control pests like the seedcorn maggot in crops such as green beans and sweet corn, with comparable or even superior efficacy to conventional neonicotinoid treatments. In addition, botanical insecticides derived from plant extracts (e.g., neem, pyrethrum) are attracting renewed interest due to their complex modes of action, which can delay the development of resistance, and their generally favorable safety profile for the environment and non-target organisms [4].

5. Conclusion

The future of insect pest control lies not in a single solution but in the strategic integration of various tools within an IPM approach.

The main research areas are as follows:

- **Precision application systems**

Advances in nano-vectors and formulation technologies aim to improve the stability and targeting of nucleic acid-based insecticides, thereby reducing required doses and costs [5].

- **Insecticide resistance management (IRM) 2.0**

Using genomic and surveillance data to model resistance evolution and define proactive insecticide rotation strategies at the landscape scale, preserving the efficacy of existing and new formulations [5].

- **Synergistic and protective agents**

Developing new compounds that inhibit insect detoxification enzymes (synergists) to restore their sensitivity to existing insecticides, or that protect beneficial arthropods (protective agents) [6].

Acknowledgement

The author acknowledges the use of Deep Seek (AI tool) for language polishing.

Author details

Farzana Khan Perveen

Sciences de la vie, sciences naturelles et biotechnologie à la Faculté de Pharmacie et Médecine. Université de Reims Champagne-Ardenne, Reims Cedex, France

*Address all correspondence to: farzanasan@hotmail.com

IntechOpen

© 2026 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

[1] Reis MRD, Fernandes FL, Lopes EA, G. JER, Alves FM. Chapter 26-Pesticide residues in coffee agroecosystems. *Coffee in Health and Disease Prevention*. 2015;235–244. DOI: 10.1016/B978-0-12-409517-5.00026-7

[2] Reiley L, Chronicle C. New pesticides provide challenging alternatives to neonicotinoids. *Cornell Chronicle*. 2025. Available from: <https://news.cornell.edu/stories/2025/08/new-pesticides-provide-challenging-alternatives-neonicotinoids> [Accessed: 2025-December-04]

[3] Pu J, Chung H. New and emerging mechanisms of insecticide resistance. *Current Opinion in Insect Science*. 2024;**63**:101184. DOI: 10.1016/j.cois.2024.101184

[4] Oberemok VV, Laikova K, Ali J, Chachoua I, Gal'chinsky N. CUADb-based oligonucleotide insecticides and RNA biocontrols: molecular bases and potential in plant protection. 2024. Available from: <https://www.biorxiv.org/content/10.1101/2024.03.13.584797v3.full.pdf> [Accessed: 2025-February-05]

[5] Head GP, Carroll MW, Evans SP, Rule DM, Willse AR, Clark TL, Storer NP, Flannagan RD, Samuel LW, Meinke LJ. Evaluation of SmartStax and SmartStaxPRO maize against Western corn rootworm and Northern corn rootworm. *Efficacy and Resistance Management. Pest Management Science*. 2017;**73**:1883–1899. DOI: 10.1002/ps.4554

[6] Welsh J. First RNA-based insecticide reaches market. *Engineering*. 2024;**43**:8–10

Chapter 2

Biodegradable, Green and Nanotechnology-Enabled Insecticides: Green Chemistry, Applications and Advances

Pavithra Deenadayalan, Pushpa Rani Vedham and Jofy Francis

Abstract

Modern agriculture faces a critical dichotomy: the imperative for global food security versus the ecological debt incurred by the inefficiency of conventional agrochemicals. This chapter explores the 'Nano-Green Nexus', a paradigm shift moving from recalcitrant synthetics to biodegradable, nanotechnology-enabled delivery systems. We critically examine the convergence of three core pillars: the phytosynthesis of metal nanoparticles, the valorisation of agricultural waste (such as lignin and chitosan) into nanocarriers, and the engineering of solvent-free formulations. Beyond material sustainability, the discussion focuses on 'smart' functionality, specifically stimuli-responsive mechanisms where release is triggered exclusively by pest-specific cues – such as alkaline gut pH or esterase activity, thereby minimising non-target toxicity. Furthermore, the text addresses the environmental fate of these materials through the 'Safe-by-Design' (SbD) framework, decoupling carrier degradation from active ingredient release to protect the soil microbiome. Finally, we analyse the 'lab-to-field' gap, evaluating regulatory hurdles and the economic 'dosage offset' required to make green nanotechnology commercially viable. The chapter concludes that integrating AI-driven polymer design with green chemistry offers a regenerative path forward, transforming pesticides from environmental pollutants into precise, nature-inspired agro-therapeutics.

Keywords: green nanopesticides, stimuli-responsive delivery, waste valorisation, safe-by-design (SbD), RNA interference (RNAi), sustainable agriculture

1. Introduction

Modern agriculture finds itself on a precarious precipice. On one side lies the undeniable imperative of global food security – the need to feed a population projected to exceed 9.7 billion by 2050 [1]. On the other hand lies the cumulative ecological debt incurred by the 'Green Revolution'. For decades, synthetic agrochemicals have served as the backbone of high-yield farming; yet, this reliance

has evolved into a formidable dilemma. While conventional pesticides prevent an estimated 30–40% yield loss annually, their ‘shoot-and-spray’ application method is fundamentally inefficient. It is an open secret in agrochemical research that less than 0.1% of applied pesticides actually reach their target pests. The remaining 99.9% is lost to runoff, volatilisation, and leaching, becoming an environmental pollutant rather than a crop protectant [2]. This massive inefficiency drives a vicious cycle of chemical loading. To compensate for losses, application rates are increased, accelerating the evolution of pest resistance – a biological arms race where pests evolve faster than we can synthesise new molecules. Furthermore, the collateral damage is severe. Broad-spectrum synthetics indiscriminately eliminate non-target organisms, including pollinators essential for crop reproduction and natural predators that keep pest populations in check. Perhaps most critically, the persistence of recalcitrant chemical residues disrupts the soil microbiome, altering nitrogen-fixing communities and degrading soil health over decades. We have reached a point of ‘chemical saturation’ where simply synthesising more potent toxins is no longer a viable strategy. The solution requires a paradigm shift not just in what we use, but how we deliver it [3, 4].

Nanotechnology has emerged as the most promising frontier to break this deadlock, offering the potential to transform conventional pesticides into ‘smart’ delivery systems. However, a critical disconnect persists: the ‘Lab-to-Field Gap’. The last decade has seen an exponential surge in publications describing novel nanopesticides, yet remarkably few have translated into commercial products or field-scale applications [5]. This gap exists because early research often focused on efficacy without considering sustainability or scalability. Many ‘first-generation’ nanopesticides utilised non-biodegradable synthetic polymers or energy-intensive synthesis methods, which merely traded one environmental problem (chemical toxicity) for another (nanopollution) [6, 7].

To bridge this gap, the field is pivoting towards a ‘Green Nanotechnology’ approach. This is not merely a rebranding exercise; it is a fundamental restructuring of pesticide design. True ‘Green Nanopesticides’ are not defined solely by the use of plant extracts. Instead, they represent a holistic, ‘Safe-by-Design’ (SbD) philosophy that integrates three core pillars: moving away from hazardous organic solvents and high-energy processes, modern protocols prioritize ‘one-pot’ bio-reduction methods where plant metabolites or microbial enzymes serve as both reducing and capping agents, minimising the carbon footprint of production; the shift from persistent synthetic polymers (like poly-caprolactone) to fully biodegradable, abundant biopolymers; and materials such as chitosan (derived from crustacean waste), zein (from corn), and lignin (a paper industry byproduct) are being repurposed as smart nanocarriers. These matrices are designed to degrade into harmless byproducts (sugars, amino acids) after delivering their payload. The incorporation of bio-based actives – such as essential oils (EOs), botanical terpenes, and the cutting-edge employment of double-stranded RNA (dsRNA) – offers high specificity and low mammalian toxicity compared to organophosphates or carbamates [8–10].

This chapter departs from standard reviews that merely catalogue the types of nanomaterials available. Instead, it provides a critical examination of the mechanisms that drive the next generation of sustainable agrochemicals. Our focus is specifically on the convergence of biodegradability and functionality, the ‘Nano-Green Nexus’. The novelty of this chapter lies in its focus on ‘Stimuli-Responsive’ and ‘Smart’ green systems. Our work emphasises that biodegradability alone is insufficient; the future

lies in nanocarriers that are biologically inert until triggered by specific environmental cues – such as the alkaline pH of an insect's gut or the presence of specific pest enzymes. This 'lock-and-key' approach ensures that the active ingredient is released only when ingested by the target pest, thereby protecting beneficial insects and the wider ecosystem. By synthesising recent advances in green chemistry, polymer science, and insect toxicology, this chapter aims to provide a blueprint for the future of crop protection. We will explore how 'Green' and 'Nano' can be integrated not just to kill pests more effectively, but to create a circular, regenerative approach to agriculture where the cure is no longer worse than the disease. The following sections will detail the fabrication, mechanistic action, and regulatory pathways of these advanced, nature-inspired systems, offering a roadmap for translating green nanoscience from the laboratory bench to the farmer's field.

2. Green chemistry principles in nanopesticide synthesis

The transition from conventional pesticide formulation to nanotechnology-enabled systems offers a unique opportunity to redesign the entire lifecycle of agrochemicals. However, if the synthesis of these 'advanced' materials relies on toxic reducing agents (e.g., sodium borohydride), volatile organic solvents (e.g., chloroform, toluene), or energy-intensive calcination, the net environmental benefit is negated. Therefore, the application of green chemistry principles – specifically atom economy, safer solvents, and design for degradation – is not merely an ethical preference but a technical prerequisite for the future of sustainable agriculture. This section explores the three pillars driving this paradigm shift: phytonanotechnology, waste valorisation, and solvent-free formulation [11, 12].

2.1 Bio-reduction and phytonanotechnology model

The synthesis of metal and metal-oxide nanoparticles (MNPs), such as silver (Ag), zinc oxide (ZnO), and copper oxide (CuO), has traditionally been a chemical-heavy process. The 'Green' alternative, often termed phytonanotechnology, leverages the complex biochemical arsenal of plants to replace hazardous industrial reagents. This approach is rooted in the dual capability of plant secondary metabolites to act as both reducing agents (converting metal ions M^+ to M^0) and capping agents (stabilising the nanoparticle to prevent agglomeration) [13, 14].

The mechanism relies on the redox potential of phytochemicals. Plant extracts are rich in polyphenols, flavonoids, terpenoids, and alkaloids. For instance, the hydroxyl (-OH) groups present in flavonoids (like quercetin or luteolin) facilitate the reduction of metal salts. In the synthesis of silver nanoparticles (AgNPs), the enol form of the flavonoid releases electrons to reduce Ag^+ ions to elemental silver (Ag^0). Simultaneously, the oxidised form of the phytochemical adsorbs onto the surface of the nascent nanoparticle. This surface adsorption is critical [15, 16]. The steric hindrance provided by these bulky biomolecules creates a 'capping layer' that dictates the size and shape of the nanoparticle. Unlike chemical capping agents (e.g., PVP or PEG), which are inert, phytomolecules often possess intrinsic insecticidal or antimicrobial properties. Thus, the resulting nanoparticle is not just a carrier but a synergistic agent, where the metal core and the biological shell work in tandem to disrupt pest physiology [17, 18].

Early green synthesis was often uncontrolled, leading to polydisperse particles (varied sizes) that performed inconsistently in the field. Current advances utilise optimised ‘one-pot’ protocols where pH, temperature, and extract concentration are fine-tuned to achieve monodispersity without external stabilisers. For example, recent studies have demonstrated the use of *Azadirachta indica* (Neem) leaf extract to synthesise zinc oxide (ZnO) nanoparticles in a single step. The process eliminates the need for intermediate purification, drastically reducing solvent waste and energy consumption. This meets the ‘Atom Economy’ principle of green chemistry, as the majority of the starting biological material is incorporated into the final functional product [19, 20].

2.2 Waste valorisation: The circular economy angle

A sustainable nanopesticide cannot utilise expensive, food-grade precursors. To be economically viable and ethically sound, the field is pivoting towards waste valorisation – upcycling agricultural and industrial byproducts into high-value nanocarriers. This approach aligns with the circular economy, turning disposal liabilities into assets. Lignin molecules are amphiphilic, allowing them to self-assemble into hollow nanospheres in aqueous solutions [21, 22]. These hydrophobic cores can encapsulate lipophilic insecticides (like pyrethroids or avermectins) with high efficiency. A major limitation of botanical insecticides, such as azadirachtin (from neem), is their rapid photodegradation; UV light breaks down the molecule within hours, rendering it useless. Lignin nanoparticles (LNPs) offer a sophisticated solution. Due to its aromatic structure, lignin possesses a high refractive index and acts as a natural broad-spectrum UV blocker. Recent SbD formulations have entrapped azadirachtin within LNPs. This is a definitive example of how green chemistry improves performance, not just safety [23].

Derived from the deacetylation of chitin (found in crustacean shells from the seafood industry), chitosan is perhaps the most versatile ‘Green’ polymer. Chitosan is polycationic (positively charged), which is crucial for targeting insect pests. The insect gut membrane is typically anionic (negatively charged). The electrostatic attraction between the chitosan nanocarrier and the pest gut enhances adhesion and retention time, significantly increasing the bioavailability of the insecticide. Researchers are now modifying chitosan with EOs (e.g., grafting cinnamaldehyde) to create ‘functionalized chitosans’ that serve as stand-alone biopesticides, eliminating the need for synthetic toxins [24]. Zein is a hydrophobic protein found in corn gluten meal, a byproduct of bioethanol and corn starch processing. Its natural hydrophobicity makes it an excellent matrix for encapsulating water-insoluble pesticides without using toxic cross-linkers like glutaraldehyde. Zein nanoparticles effectively protect sensitive active ingredients from hydrolysis and enzymatic breakdown in the soil, offering a ‘slow-release’ profile that matches the pest lifecycle [25].

2.3 Solvent-free formulation techniques

The final pillar of green synthesis is the elimination of hazardous solvents during the formulation stage. Traditional encapsulation (e.g., solvent evaporation method) often requires large volumes of organic solvents to dissolve the polymer and pesticide. Even with rigorous drying, trace residues can remain, posing toxicity risks.

Modern ‘Green Engineering’ techniques utilise physical forces rather than chemical solvents to create nanostructures [13].

High pressure homogenization (HPH) is a top-down approach that relies on extreme shear stress, turbulence, and cavitation to reduce particle size. A coarse emulsion of the lipid/polymer and water is forced through a microscopic gap at high pressures (often exceeding 1,000 bar). The immense physical energy shatters the droplets into the nanoscale range. This process is typically water-based and solvent-free. It is particularly effective for producing solid lipid nanoparticles (SLNs) and nanoemulsions. HPH is also highly scalable; unlike chemical synthesis, which is often batch-dependent, HPH can be run continuously, making it suitable for industrial-scale production of green nanopesticides [26].

Supercritical fluids are substances at a temperature and pressure above their critical point, where distinct liquid and gas phases do not exist. Supercritical carbon dioxide (scCO₂) is the gold standard in this domain. scCO₂ acts as a ‘Green Solvent’. It has the density of a liquid (good for dissolving active ingredients) but the viscosity of a gas (high diffusivity). In the rapid expansion of supercritical solutions (RESS) process, the pesticide and polymer are dissolved in scCO₂ and then rapidly depressurised through a nozzle. The sudden drop in pressure causes the CO₂ to revert to a gas instantly, leaving behind dry, solvent-free nanoparticles. The process operates at relatively low temperatures, preventing the thermal degradation of heat-sensitive botanical pesticides. Furthermore, since CO₂ simply evaporates, the final product is 100% solvent-free, meeting the strictest regulatory standards for organic farming inputs [27, 28].

The integration of bio-reduction, waste valorisation, and solvent-free engineering represents the maturity of the nanopesticide field. We are moving beyond the ‘novelty’ of simply making things small, towards a sophisticated design philosophy where every component, from the reducing agent to the carrier matrix, is selected for its environmental compatibility and economic efficiency. This holistic adherence to green chemistry principles ensures that the next generation of insecticides will be potent against pests but benign to the planet.

3. Novel formulations and smart delivery systems

If green chemistry principles represent the ‘hardware’ of sustainable agriculture – providing the eco-friendly materials – then formulation science is the ‘software’. It is the programming code that dictates how, when, and where an active ingredient interacts with a biological system. For decades, the agrochemical industry relied on ‘dumb’ formulations: emulsifiable concentrates or wettable powders designed solely for immediate, massive dispersal. The result was a shotgun approach, where efficacy relied on flooding the ecosystem. The current frontier, however, is defined by precision [29]. We are moving towards smart delivery systems (SDS) that mimic the sophistication of pharmaceutical drug delivery. This transition focuses on three critical objectives: enhancing the solubility of hydrophobic actives, protecting labile molecules from environmental degradation, and, most critically, engineering ‘stimuli-responsive’ mechanisms that release the payload only upon recognising a specific biological target. This section evaluates the primary vehicles driving this shift and the next-generation payloads they carry [30, 31].

3.1 The three big green carriers: Biopolymers, lipids, and nanoemulsion

The choice of a nanocarrier is never arbitrary; it is a compromise between loading capacity, stability, and release profile. While hundreds of materials exist, three distinct classes have emerged as the frontrunners for commercial scalability due to their biodegradability and low environmental footprint. A biopolymeric nanoparticle is the architecture of entrapment, biopolymers are the workhorses of green formulation. Unlike synthetic polyesters, which often require toxic catalysts, biopolymers like chitosan, alginate, and cellulose derivatives offer intrinsic biological compatibility [32, 33]. Chitosan, a cationic polysaccharide, is arguably the most valuable material in the insecticidal arsenal. Its primary advantage is not just its abundance (derived from crustacean waste) but its charge. Most plant surfaces and insect gut linings are anionic (negatively charged). Chitosan nanoparticles possess a high positive zeta potential, allowing them to adhere strongly to leaves (resisting rain fastness) and bind to the insect midgut. This mucoadhesion significantly increases the residence time of the insecticide, allowing for greater absorption. Furthermore, the reactive amine ($-NH_2$) groups on the chitosan backbone allow for easy surface modification, turning the particle into a customizable platform. While chitosan handles cationic needs, alginate (from brown seaweed) provides an anionic counterpart [34]. Alginate nanoparticles are synthesised through simple ionotropic gelation with calcium ions (Ca^{2+}), creating a rigid ‘egg-box’ structure that is excellent for encapsulating heat-sensitive EOs. Nanocellulose (specifically cellulose nanocrystals), on the other hand, offers exceptional mechanical strength. It acts as a reinforcing ‘Green’ filler, creating robust barriers that slow down the diffusion of volatile pesticides, extending their field life from hours to days [35, 36]. SLNs: The ‘Green’ lipid matrix, while polymeric systems are effective, they often suffer from ‘burst release’ – dumping their payload too quickly. SLNs offer a solution. Imagine a solid fat droplet (made of biodegradable waxes like beeswax or carnauba wax) stabilised by green surfactants. Unlike liquid emulsions, the lipid core remains solid at room temperature. This solid matrix effectively immobilises the active ingredient, restricting its mobility and protecting it from chemical hydrolysis. For lipophilic insecticides (which include the vast majority of synthetics and botanicals), SLNs are the ideal carrier. They mimic the natural waxy cuticle of leaves, facilitating trans-laminar transport. Moreover, because they are composed of physiological lipids, their degradation products are simply fatty acids, which are readily metabolised by soil microorganisms without toxic residue. Kinetic stability for EOs and nanoemulsions are distinct from SLNs in that the core remains liquid. These are oil-in-water dispersions with droplet sizes typically below 200 nm. They are particularly vital for the delivery of EOs. EOs are potent botanical insecticides but are highly volatile and prone to oxidation. By encapsulating EOs in a high-energy nanoemulsion, we achieve two things. First, the massive increase in surface area improves the interaction with the insect cuticle, often dissolving the waxy protective layer of the pest and causing desiccation. Second, the formulation renders the water-insoluble oils compatible with aqueous spray tanks, eliminating the need for heavy organic solvents in the application process [37–39].

3.2 Stimuli responsive release

The most significant advancement in recent literature is the shift from ‘Passive Release’ (diffusion-controlled) to ‘Active/Triggered Release’. This is the ‘smart’ aspect of the technology. The goal is to design a nanocarrier that remains hermetically sealed during storage and application but disassembles instantly when it encounters the unique microenvironment of a pest. This SbD approach minimises exposure to non-target organisms like bees or earthworms [40]. Most mammals and beneficial pollinators have acidic to neutral gut environments. In stark contrast, the midgut of lepidopteran pests (caterpillars, bollworms) is highly alkaline, with pH levels often exceeding the optimum limit. We can exploit this evolutionary trait by designing pH-sensitive polymers. For instance, nanoparticles formulated with poly(methacrylic acid) or specific carboxylated polysaccharides remain collapsed and tightly bound at neutral pH (on the leaf surface) [41, 42]. Enzyme-triggered release follows the lock-and-key approach, targeting the pest’s enzymatic profile more specifically. Insects rely on particular enzymes – proteases, esterases, and glycosidases – to digest food. A ‘smart’ nanocarrier can be constructed using cross-linkers that serve as substrates for these enzymes. For example, if a pest species overexpresses esterase enzymes to detoxify chemicals, we can design a nanocapsule cross-linked with ester bonds. When the pest ingests the capsule, its own defence enzymes attack the shell, breaking it open and releasing the insecticide. This ‘suicide substrate’ mechanism epitomises specificity; the pesticide remains inert until the pest attempts to digest it [43].

3.3 Next generation payload: RNAi technology

As we reach the limits of chemical toxicity, the field is looking towards genetic intervention. RNA interference (RNAi) represents the cutting edge of crop protection. Instead of poisoning the insect, we introduce dsRNA sequences that match a vital gene in the pest (e.g., a gene essential for moulting or metabolism). When the insect cells absorb this dsRNA, their internal machinery silences that specific gene, causing death. However, ‘naked’ dsRNA is incredibly fragile. UV light, rain, and ubiquitous soil enzymes (RNases) degrade it within hours [44]. Furthermore, the insect gut is a harsh environment that destroys genetic material before it can be absorbed. This is where green nanotechnology becomes an enabler of biotechnology. The Chitosan-dsRNA Complex. This is where the unique properties of chitosan find their highest calling. Since DNA/RNA is negatively charged (due to phosphate groups) and chitosan is positively charged, they self-assemble into tight poly-electrolyte complexes (PECs). The chitosan shell protects the delicate dsRNA from enzymatic degradation in the environment. More importantly, it facilitates ‘Endosomal Escape’. When an insect cell ingests the nanoparticle, it is trapped in an acidic vesicle called an endosome. Chitosan acts as a ‘proton sponge’, absorbing protons and swelling until it bursts the endosome, releasing the dsRNA into the cytoplasm, where it can initiate gene silencing [45, 46].

The evolution from simple emulsions to enzyme-triggered gene-silencing vectors marks a maturation of the field. We are no longer simply packaging poisons; we are engineering intelligent devices that navigate biological barriers. By coupling the biodegradability of green carriers with the specificity of stimuli-responsive release, we are finally closing the gap between the laboratory promise of nanotechnology and the field-level demands of sustainable **Table 1** agriculture.

S. No	Nanocarrier Class	Source material	Synthesis method	Biodegradability profile	Key Advantages	Limitations	Reference
1	Polysaccharide (cationic)	Chitosan (crustacean shell waste/chitin)	Ionic gelation: cross-linking with TPP (tripolyphosphate); solvent-free.	Rapid: enzymatic breakdown by soil chitinases/lysozymes (<14 days).	Mucoadhesion: positive charge binds to the anionic insect gut; the proton sponge effect aids RNAi delivery.	Low solubility in neutral/alkaline pH; requires a weak acid for dissolution.	[38, 47, 48]
2	Polysaccharide (anionic)	Alginate (brown algae/seaweed)	Ionotropic gelation: cross-linking with calcium ions (Ca ²⁺); Aqueous based.	High: rapid degradation in phosphate-rich soils due to cation exchange.	'Egg-Box' structure: Excellent protection for heat-sensitive essential oils; pH-responsive swelling.	High porosity can lead to premature 'burst release' of small molecules.	[23, 47]
3	Plant protein	Zein (Corn gluten meal byproduct)	Phase separation: anti-solvent precipitation (using water/ethanol); surfactant-free.	Moderate: proteolytic breakdown by soil microbes (20–40 days).	Hydrophobicity: superior encapsulation of lipophilic pesticides; naturally repels moisture during storage.	Brittle nature often requires a plasticizer, like glycerol, for film formation.	[25, 49, 50]
4	Lignocellulosic	Lignin (paper industry/kraft waste)	Acid precipitation: pH shift from alkaline to acidic; self-assembly.	Slow/moderate: degrades via fungal laccases; forms humus (45–60 days).	UV shielding: the aromatic structure absorbs UV radiation, protecting photosensitive AIs (e.g., pyrethrins).	Dark color may stain crops; variability in purity depends on the waste source.	[22, 51]
5	Solid lipid	Beeswax/carnauba wax (natural apiary/plant waxes)	High-pressure homogenisation: Hot melt dispersion; organic solvent-free.	High: lipase-mediated hydrolysis into fatty acids (less than 30 days).	Solvent-free: zero toxicity; solid matrix minimizes chemical hydrolysis of the active ingredient.	Lower loading capacity compared to polymeric systems; risk of particle gelation.	[38, 52]
6	Nanoclay composite	Halloysite nanotubes (HNTs) (natural aluminosilicate clay)	Vacuum loading: physical entrapment into the lumen; 'Green' physical process.	Inorganic/biocompatible: breaks down into basic soil minerals (\$Al\$, \$Si\$) over years.	Tubular geometry: high aspect ratio allows massive loading capacity and acts as a physical barrier to pests.	Non-biodegradable in the strict sense (mineralization), but environmentally inert.	[53, 54]
7	Microbial polyester	PHB (polyhydroxybutyrate) (bacterial fermentation)	Emulsion-solvent evaporation: Using non-toxic esters; biosynthesis.	Complete: fully metabolizable by soil bacteria into \$CO_2\$ and water (3–6 months).	Plastic-like properties: high mechanical strength and thermal stability; a true alternative to synthetic plastics.	High production costs compared to starch or cellulose-based carriers.	[55, 56]
8	Inorganic green metal	Biosynthesized silver (AgNPs) (plant leaf extract-mediated)	Photoreduction: 'One-pot' synthesis using flavonoids as reducing/capping agents.	Reactive: Slowly oxidizes to release Ag ⁺ ions; eventually precipitates as insoluble sulfides.	Dual Action: The carrier itself is antimicrobial/insecticidal; synergistic effect with the loaded pesticide.	Potential toxicity to non-target soil bacteria (nitrogen fixers) at high doses.	[57, 58]

Table 1.
Comparative analysis of biodegradable nanocarriers used in insecticide delivery.

4. Biodegradability and environmental fate

The introduction of any novel material into the agro-ecosystem carries the burden of proof regarding its persistence. For decades, the ‘legacy toxicity’ of organochlorines and recalcitrant polymers has haunted soil conservation efforts. As we transition to nanotechnology-enabled agriculture, we must rigorously ensure that we are not solving an efficacy problem while creating a new contamination crisis. The core promise of green nanopesticides is not merely that they work better, but that they ‘fail’ gracefully, breaking down into benign constituents once their biological function is complete. This section dissects the mechanistic fate of these materials in the pedosphere (soil environment) [59, 60].

4.1 Degradation pathways: Carrier and payloads

To accurately model environmental fate, we must distinguish between the degradation kinetics of the nanocarrier and the active ingredient, as they follow distinct yet interconnected pathways. The ‘Green’ advantage lies in the specific breakdown mechanisms of the matrix; biopolymeric and lipid-based carriers undergo rapid hydrolysis and enzymatic depolymerisation – such as chitinases cleaving chitosan into glucosamine – ultimately achieving full mineralisation into CO₂, water, and microbial biomass [61]. This creates a novel ‘bi-phasic’ degradation profile where the active ingredient is initially shielded from abiotic stressors, artificially extending its half-life during the protection phase, before being released into the soil solution as the matrix disintegrates. By controlling this release, we avoid the ecologically damaging concentration spikes associated with conventional formulations, allowing the soil’s natural detoxification pathways to process the active ingredient without being overwhelmed [62].

4.2 Impact on soil microbiome: The nitrogen fixer benchmark

The ecological safety of nanopesticides is best adjudicated by their impact on plant-beneficial bacteria (PBB), specifically nitrogen-fixing *Rhizobium* and phosphate-solubilising genera. Recent metagenomic analyses highlight a critical divergence between ‘hard’ inorganic nanoparticles, which often exhibit broad-spectrum bactericidal activity, and ‘soft’ green nanocarriers, which demonstrate selective safety. Unlike synthetic carbamates that can decimate beneficial populations, green carriers like zein and alginate have shown negligible toxicity towards Gram-negative soil flora; in some instances, the oligosaccharide breakdown products of these biopolymers even act as ‘prebiotics’, temporarily stimulating microbial metabolic activity [63, 64]. However, safety is not intrinsic but engineered; surface shielding strategies, such as coating cationic particles with neutral polymers, are increasingly employed to prevent electrostatic disruption of bacterial membranes, ensuring the formulation targets the pest without sterilising the soil microbiome [65, 66].

4.3 The ‘Safe-by-Design’ (SbD) concept

The ultimate regulatory safeguard in modern agro-nanotechnology is the SbD framework, which prioritizes the programmed loss of ‘nano’ characteristics

immediately post-application to prevent bioaccumulation. The primary risk of nanomaterials often stems from their physical size, specifically their ability to penetrate biological barriers rather than their chemical composition [67]. To mitigate this, green delivery systems are engineered to be thermodynamically unstable in the environment; triggered by soil ions or UV exposure, these particles undergo rapid aggregation, clumping into micron-sized entities that can no longer breach cell membranes. This 'self-destruct' mechanism ensures that while the chemical efficacy persists long enough to control the pest, the physical nanohazard is eliminated almost instantly, effectively preventing the long-term persistence and trophic transfer that plague non-biodegradable synthetic polymers [68, 69].

5. Regulatory challenges and commercial hurdles

The transition of green nanopesticides from the petri dish to the plough is not merely a scientific challenge; it is a regulatory and economic labyrinth. While the laboratory data are compelling, showing higher efficacy and lower environmental toxicity, the commercial landscape is fraught with uncertainty. The agrochemical industry is heavily regulated, and for good reason. However, the current legislative frameworks were designed for bulk chemicals, not for 'smart' dynamic systems. This disconnect creates a 'Grey Area' that stifles innovation and complicates the path to market for even the most sustainable technologies [70].

5.1 The 'nano' regulatory grey area: A legislative lag

The fundamental problem facing regulatory bodies like the US Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA) is the definition of 'risk' at the nanoscale. Traditional toxicology relies on mass-based metrics (e.g., mg/kg). However, the toxicity of a nanomaterial is often a function of its surface area, charge, and particle number, not just its mass [71]. A 'Green' chitosan nanoparticle might be chemically identical to bulk chitosan (which is Generally Recognised as Safe or GRAS), but its nanoformulation enables it to cross biological barriers that the bulk material cannot. Under current European Food Safety Authority (EFSA) guidelines, if a manufacturer takes an approved botanical active (like neem oil) and encapsulates it in a nanoparticle, the entire formulation is treated as a new chemical entity. This triggers a requirement for a completely new set of ecotoxicological dossiers, including chronic toxicity, genotoxicity, and fate modelling, which can cost millions and take up to five to seven years to compile [64, 72]. For a small startup developing a green formulation, this barrier is often insurmountable. The 'Grey Area' here is the lack of a 'Grouping/Read-Across' framework, where safe green carriers (like alginate or zein) could theoretically be fast-tracked based on existing safety data. Until such a framework is formalised, the regulatory burden remains disproportionately high for sustainable innovations [73, 74].

The EPA and FIFRA: a case-by-case slowdown. In the United States of America, pesticides are regulated under Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). The EPA has taken a 'case-by-case' approach to nanopesticides. While this allows for flexibility, it creates massive market uncertainty. The EPA currently classifies nanopesticides as 'new active ingredients' if the nanoscale form exhibits novel properties compared to the bulk counterpart [75]. This is a double-edged sword.

The very ‘novelty’ we tout in this chapter – enhanced solubility, stimuli-responsive release – is exactly what triggers heightened regulatory scrutiny. The industry is currently in a deadlock: companies are hesitant to invest in ‘smart’ release mechanisms because they fear the EPA will require indeterminate amounts of safety data to prove that these ‘smart’ particles won’t behave unpredictably in the environment [67].

5.2 Cost-benefit analysis: The economic viability of ‘Green’

While the manufacturing cost of green nanopesticides – driven by purified biopolymers and high-energy homogenization processes – can exceed that of mass-produced synthetics by a factor of three to five, this ‘per kilogram’ comparison is economically misleading in the context of nanotechnology. The true commercial viability rests on the ‘Dosage Offset’, a paradigm where the superior bioavailability and environmental stability of nanoencapsulated actives allow for a drastic reduction in application rates [76]. Furthermore, when factoring in the ‘hidden’ economic benefits – such as reduced fuel costs from less frequent spraying, the premium value of residue-free produce, and the ability of complex botanical/RNAi payloads to break costly resistance cycles – green nanopesticides emerge not merely as an ethical luxury, but as a superior economic investment that offers farmers ‘efficacy insurance’ against the diminishing returns of conventional chemical loading [77].

The commercialisation of biodegradable, green nanopesticides **Table 2** is currently bottlenecked not by a lack of science but by a regulatory apparatus struggling to catch up with innovation and a market that is slowly learning to value efficiency over volume. The path forward requires a synchronized effort: regulators must establish clear ‘nanospecific’ safety corridors for biopolymers to lower the barrier to entry, and scientists must rigorously demonstrate the ‘Dosage Offset’ in large-scale field trials to prove to farmers that ‘Green’ is not just a luxury but a prudent economic investment (**Figure 1**).

6. Conclusion

The trajectory of modern crop protection is currently undergoing a fundamental phase transition, moving from the era of ‘blunt force’ chemical saturation to an age of precision biophysics. As synthesised in this chapter, the convergence of green chemistry and nanotechnology has successfully demonstrated that efficacy and environmental safety are not mutually exclusive; through the use of stimuli-responsive biopolymers and waste-derived nanocarriers, we can now engineer systems that are lethal to pests yet benign to the biosphere. However, the horizon of this field extends far beyond simple substitution. The immediate future lies in multifunctional co-encapsulation, where the ‘nanopesticide’ evolves into a holistic ‘agro-therapeutic’ device. We are rapidly moving towards ‘all-in-one green particles’ that simultaneously encapsulate insecticides and macronutrients (NPK fertilisers), creating a synergistic delivery system that protects the crop while nourishing it – effectively reducing the number of field interventions required by the farmer. To manage the immense chemical complexity of these multi-payload systems, the field is increasingly pivoting towards artificial intelligence (AI) and machine learning (ML). The traditional ‘trial-and-error’ approach to polymer selection is being replaced by high-throughput computational screening, where ML algorithms predict

Sl. No	Stimulus/ trigger	Nanoformulation	Active ingredient (AI)	Target mechanism	Enhanced Efficacy	Reference
1	Alkaline pH (pH >9.0)	Silica-coated pectin nanoparticles	Indoxacarb	Carboxyl groups on pectin deprotonate in the alkaline lepidopteran gut, causing swelling and rapid toxin release.	Increased photostability by 40%; negligible toxicity to bees (neutral gut).	[42, 78]
2	Enzyme (esterase)	Nanocapsules	Bt toxin (Cry1Ac)	Surface cross-linkers are specific substrates for pest esterases; the capsule degrades only when attacked by gut enzymes.	Reduced LC50 by 10-fold compared to non-targeted formulations.	[43, 79]
3	Light (UV–A/Visible)	Lignin-grafted-polydopamine (LNP)	Abamectin	Aromatic rings absorb UV light; the coating degrades slowly under solar radiation to provide sustained release.	Extended active half-life from 18 hours to 7 days under field conditions.	[80]
4	Redox (glutathione)	Disulfide-cross-linked Chitosan	Imidacloprid	Disulfide bonds (–S–S–) cleave in the high-GSH reducing environment of insect cells, releasing the payload intracellularly.	3.5x higher cellular uptake efficacy in resistant aphid cell lines.	[81, 82]
6	Microbial (chitinase)	Mesoporous silica-chitosan gatekeeper	Validamycin	Chitosan ‘cap’ blocks pores; degradation by fungal pathogen chitinases opens pores to release fungicide/ insecticide.	‘On-demand’ release prevents leaching; 60% reduction in total dosage required.	[83, 84]
8	Gene silencing (RNAi)	Star-polycationic Chitosan	dsRNA (targeting ATPase)	High positive charge protects dsRNA from soil nucleases; the Proton Sponge’ effect triggers endosomal escape inside pest cells.	85% gene silencing efficiency observed in Spodoptera litura larvae.	[45, 65]

Table 2.
Recent breakthroughs in stimuli-responsive and green nanopesticides.

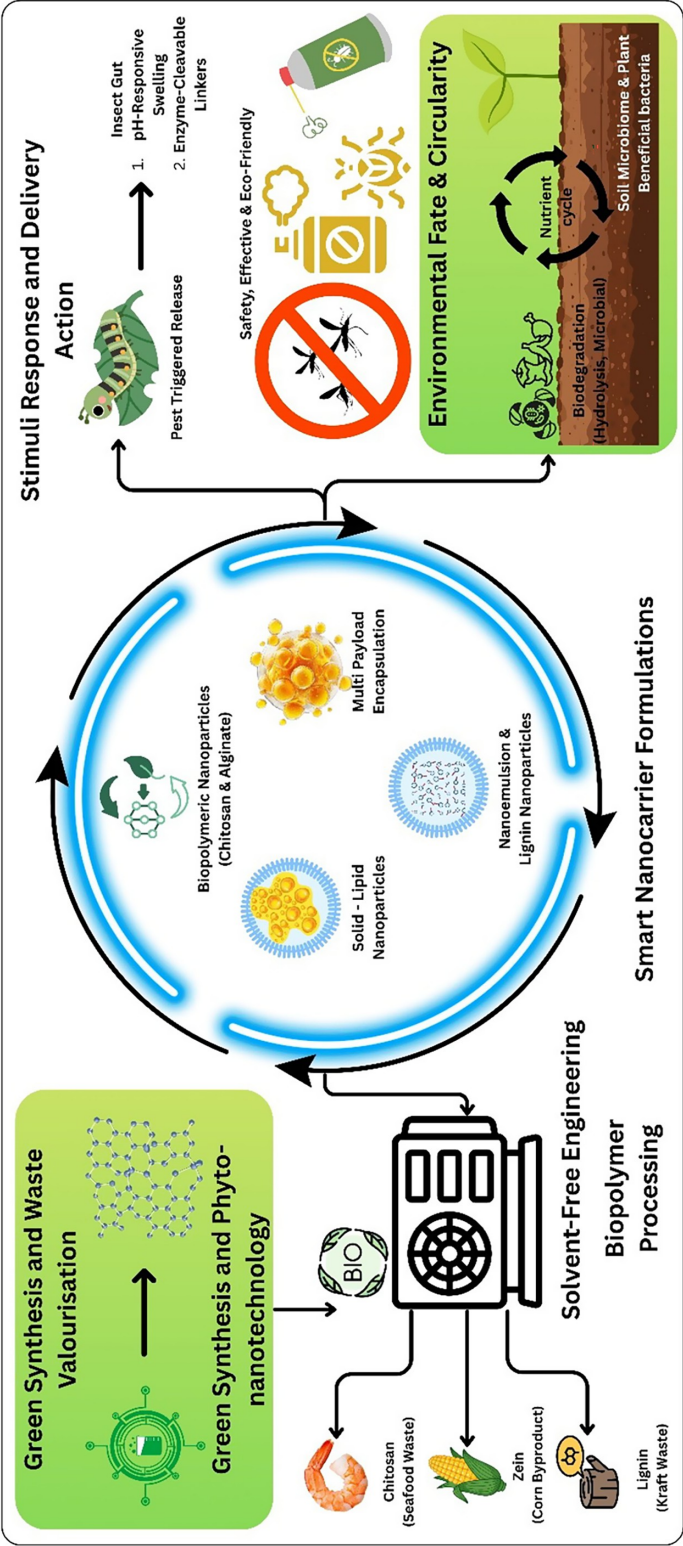


Figure 1. Schematic illustration of the 'Nano-Green Nexus', depicting the conversion of agricultural waste into smart, stimuli-responsive nanocarriers that ensure pest-specific targeting and eco-friendly soil biodegradation.

the degradation kinetics and encapsulation efficiency of thousands of biopolymer combinations in silico before a single beaker is mixed. This digital acceleration is critical for designing 'hyper-specific' carriers tailored to local soil conditions and specific pest enzymes. Ultimately, the 'Green Nano' revolution is not merely about making smaller pesticides; it is about establishing a circular, regenerative agricultural paradigm. By closing the loop – using agricultural waste to protect agriculture's future – and strictly adhering to SbD principles, we are laying the foundation for a sustainable food system where technology mimics the resilience and efficiency of nature itself, finally bridging the chasm between high-yield requirements and ecological stewardship.

Author details

Pavithra Deenadayalan, Pushpa Rani Vedham* and Jofy Francis
Department of Advanced Zoology and Biotechnology, Loyola College, Chennai,
India

*Address all correspondence to: pushparani@loyolacollege.edu

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Ahtisham M, Obaid F, Ammar H. Advancing modern agriculture: Integrating sustainable practices for a resilient future. *Premier Journal of Plant Biology*. 2025. DOI: 10.70389/PJPB.100015
- [2] Das S, et al. Green chemistry approaches in agrochemical development: Towards eco-friendly pesticides. *Oriental Journal Of Chemistry*. 2025;**41**(4):1362–1376. DOI: 10.13005/OJC/410435
- [3] Altofan NKN, Alawadi MA, Hameed DB. Beyond chemical pesticides: Harnessing biological agents and molecular technologies for sustainable insect pest management. *European Journal of Ecology, Biology and Agriculture*. 2025;**2**(4):92–101. DOI: 10.59324/EJEBA.2025.2(4).08
- [4] Ray P, Lakshmanan V, Labbé JL, Craven KD. Microbe to microbiome: A paradigm shift in the application of microorganisms for sustainable agriculture. *Frontiers in Microbiology*. 2020;**11**:622926. DOI: 10.3389/FMICB.2020.622926/FULL
- [5] Kumar S, Nehra M, Dilbaghi N, Marrazza G, Hassan AA, Kim K-H. Nano-based smart pesticide formulations: Emerging opportunities for agriculture. *Journal of Controlled Release*. 2019;**294**:131–153. DOI: 10.1016/J.JCONREL.2018.12.012
- [6] Vinci G, Savastano M, Restuccia D, Ruggeri M. Nanobiopesticides: Sustainability aspects and safety concerns. *Environments*. 2025;**12**(3):74. DOI: 10.3390/ENVIRONMENTS12030074
- [7] Wang D, et al. Nano-enabled pesticides for sustainable agriculture and global food security. *Nature Nanotechnology*. 2022;**17**(4): 347–360. DOI: 10.1038/s41565-022-01082-8
- [8] Pouthika K, Madhumitha G. A review on plant-derived nanomaterials: An effective and innovative insect-resistant strategy for alternate pesticide development. *International Journal of Environmental Science and Technology*. 2024;**21**(2):2239–2262. DOI: 10.1007/S13762-023-04998-3
- [9] Kumar R, et al. Advances in biopolymeric nanopesticides: A new eco-friendly/eco-protective perspective in precision agriculture. *Nanomaterials*. 2022;**12**(22):3964. DOI: 10.3390/NANO12223964
- [10] You C, et al. Advances in the design of functional cellulose based nanopesticide delivery systems. *Journal of Agricultural and Food Chemistry*. 2024;**72**(20):11295–11307. DOI: 10.1021/ACS.JAFC.4C00698
- [11] Pirzadah TB, et al. Development of nano-formulations via green synthesis approach. *Nanotechnology in the Life Sciences*. 2020:171–183. DOI: 10.1007/978-3-030-39978-8_10
- [12] Bartolucci C, et al. Green nanomaterials fostering agrifood sustainability. *TrAC Trends in Analytical Chemistry*. 2020;**125**:115840
- [13] Singh J, Dutta T, Kim K-H, Rawat M, Samddar P, Kumar P. “Green” synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*. 2018;**16**(1): 84. DOI: 10.1186/S12951-018-0408-4

- [14] Villagrán Z, et al. Plant-based extracts as reducing, capping, and stabilizing agents for the green synthesis of inorganic nanoparticles. *Resources*. 2024;**13**(6):70. DOI: 10.3390/RESOURCES13060070
- [15] Rajeshkumar S, Bharath LV. Mechanism of plant-mediated synthesis of silver nanoparticles – A review on biomolecules involved, characterisation and antibacterial activity. *Chemico-Biological Interactions*. 2017;**273**:219–227. DOI: 10.1016/J.CBI.2017.06.019
- [16] Jain S, Mehata MS. Medicinal plant leaf extract and pure flavonoid mediated green synthesis of silver nanoparticles and their enhanced antibacterial property. *Scientific Reports*. 2017;**7**(1):15867. DOI: 10.1038/s41598-017-15724-8
- [17] Javed R, Sajjad A, Naz S, Sajjad H, Ao Q. Significance of capping agents of colloidal nanoparticles from the perspective of drug and gene delivery, bioimaging, and biosensing: An insight. *International Journal of Molecular Sciences*. 2022;**23**(18):10521. DOI: 10.3390/IJMS231810521
- [18] S., V, A., K, S. S., & T, C. Nanotechnology in insect pest management: Advances, challenges, and future perspectives. *International Journal of Advanced Biochemistry Research*. 2024;**8**(9S):20–31. DOI: 10.33545/26174693.2024.V8.I9SA.2046
- [19] Kapoor N, Singh A, Khilari K, Sengar RS, Kumar R. Green synthesis of zinc oxide nanoparticles by *Azadirachta indica* L. and its optimization and characterizations. *International Journal of Agricultural Invention*. 2024;**9**(1):228–235. DOI: 10.46492/IJAI/2024.9.1.28
- [20] Golipalle AB, Nimbal SK, Desai S. Plant-based synthesis of ZnO nanoparticles using neem leaves. *International Journal of Innovative Science and Research Technology*. 2025;306–310. DOI: 10.38124/IJISRT/25JUL231
- [21] Schiavi D, Di Lorenzo V, Francesconi S, Giovagnoli S, Camaioni E, Balestra GM. Waste valorization by nanotechnology approaches for sustainable crop protection: A mini review. *IOP Conference Series: Materials Science and Engineering*. 2022;**1265**(1):012009. DOI: 10.1088/1757-899X/1265/1/012009
- [22] Rodrigues JS, Takeshita V, Campos EVR, de Freitas ASM, de Lima VH, Fraceto LF. Lignocellulosic biomass in nanopesticides: A path toward sustainable agriculture. *ACS Sustainable Chemistry & Engineering*. 2024;**12**(27):10045–10067. DOI: 10.1021/ACSSUSCHEMENG.4C01213
- [23] Flores-Céspedes F, Martínez-Domínguez GP, Villafranca-Sánchez M, Fernández-Pérez M. Preparation and characterization of azadirachtin alginate-biosorbent based formulations: Water release kinetics and photodegradation study. *Journal of Agricultural and Food Chemistry*. 2015;**63**(38):8391–8398. DOI: 10.1021/ACS.JAFC.5B03255
- [24] Abenaim L, Conti B. Chitosan as a control tool for insect pest management: A review. *Insects*. 2023;**14**(12):949. DOI: 10.3390/INSECTS14120949
- [25] Hao L, Lin G, Chen C, Zhou H, Chen H, Zhou X. Phosphorylated zein as biodegradable and aqueous nanocarriers for pesticides with sustained-release and anti-UV properties. *Journal of Agricultural and Food Chemistry*. 2019;**67**(36):9989–9999. DOI: 10.1021/ACS.JAFC.9B03060

- [26] Hidajat MJ, Jo W, Kim H, Noh J. Effective droplet size reduction and excellent stability of limonene nanoemulsion formed by high-pressure homogenizer. *Colloids and Interfaces*. 2020;**4**(1):5. DOI: 10.3390/COLLOIDS4010005
- [27] Türk M. Particle synthesis by rapid expansion of supercritical solutions (RESS): Current state, further perspectives and needs. *Journal of Aerosol Science*. 2022;**161**:105950. DOI: 10.1016/J.JAEROSCI.2021.105950
- [28] Lim KT, Ganapathy HS, Hwang HS, Kim JT, Ju CS, Johnston KP. Novel semiconducting polymer particles by supercritical fluid process. *Macromolecular Rapid Communications*. 2005;**26**(22):1779–1783. DOI: 10.1002/MARC.200500438
- [29] Xiao D, Wu H, Zhang Y, Kang J, Dong A, Liang W. Advances in stimuli-responsive systems for pesticides delivery: Recent efforts and future outlook. *Journal of Controlled Release*. 2022;**352**:288–312. DOI: 10.1016/J.JCONREL.2022.10.028
- [30] Shishir MRI, et al. Advances in smart delivery of food bioactive compounds using stimuli-responsive carriers: Responsive mechanism, contemporary challenges, and prospects. *Comprehensive Reviews in Food Science and Food Safety*. 2021;**20**(6):5449–5488. DOI: 10.1111/1541-4337.12851
- [31] Xu T, et al. Enhancing agrichemical delivery and plant development with biopolymer-based stimuli responsive core-shell nanostructures. *ACS Nano*. 2022;**16**(4):6034–6048. DOI: 10.1021/ACSNANO.1C11490
- [32] Nitta SK, Numata K. Biopolymer-based nanoparticles for drug/gene delivery and tissue engineering. *International Journal of Molecular Sciences*. 2013;**14**(1):1629–1654. DOI: 10.3390/IJMS14011629
- [33] Vodyashkin AA, Kezimana P, Vetcher AA, Stanishevskiy YM. Biopolymeric nanoparticles–multifunctional materials of the future. *Polymers*. 2022;**14**(11):2287. DOI: 10.3390/POLYM14112287
- [34] Mohan K, et al. Chitosan-based insecticide formulations for insect pest control management: A review of current trends and challenges. *International Journal of Biological Macromolecules*. 2024;**280**:135937
- [35] Huq T, et al. Nanocrystalline cellulose (NCC) reinforced alginate based biodegradable nanocomposite film. *Carbohydrate Polymers*. 2012;**90**(4):1757–1763. DOI: 10.1016/J.CARBPOL.2012.07.065
- [36] Ureña-Benavides EE, Brown PJ, Kitchens CL. Effect of jet stretch and particle load on cellulose nanocrystal–alginate nanocomposite fibers. *Langmuir*. 2010;**26**(17):14263–14270. DOI: 10.1021/LA102216V
- [37] Nguyen HM, Hwang IC, Park JW, Park HJ. Enhanced payload and photoprotection for pesticides using nanostructured lipid carriers with corn oil as liquid lipid. *Journal of Microencapsulation*. 2012;**29**(6):596–604. DOI: 10.3109/02652048.2012.668960
- [38] Nguyen HM, Hwang IC, Park JW, Park HJ. Photoprotection for deltamethrin using chitosan-coated beeswax solid lipid nanoparticles. *Pest Management Science*. 2012;**68**(7):1062–1068. DOI: 10.1002/ps.3268

- [39] Lai F, Wissing SA, Müller RH, Fadda AM. *Artemisia arborescens* L essential oil-loaded solid lipid nanoparticles for potential agricultural application: Preparation and characterization. *AAPS PharmSciTech*. 2017;7(1):2. DOI: 10.1208/PT070102
- [40] Ma C, et al. Recent advances in stimulus-responsive nanocarriers for pesticide delivery. *Journal of Agricultural and Food Chemistry*. 2024. DOI: 10.1021/ACS.JAFC.4C00997
- [41] Christiaens O, Tardajos MG, Reyna ZLM, Dash M, Dubrue P, Smagghe G. Increased RNAi efficacy in *Spodoptera exigua* via the formulation of dsRNA with guanylated polymers. *Frontiers in Physiology*. 2018;9(APR):342048. DOI: 10.3389/fphys.2018.00316
- [42] Wang S, et al. Indoxacarb-loaded anionic polyurethane blend with sodium alginate improves pH sensitivity and ecological security for potential application in agriculture. *Polymers*. 2020;12(5):1135. DOI: 10.3390/POLYM12051135
- [43] Santiana JJ, Sui B, Gomez N, Rouge JL. Programmable peptide-cross-linked nucleic acid nanocapsules as a modular platform for enzyme specific cargo release. *Bioconjugate Chemistry*. 2017;28(12):2910–2914. DOI: 10.1021/ACS.BIOCONJCHEM.7B00629
- [44] Zhang J, Khan SA, Heckel DG, Bock R. Next-generation insect-resistant plants: RNAi-mediated crop protection. *Trends in Biotechnology*. 2017;35(9):871–882. DOI: 10.1016/j.tibtech.2017.04.009
- [45] Liu Y, et al. Chitosan nanoparticle-mediated delivery of dsRNA for enhancing RNAi efficiency in *Locusta migratoria*. *Pest Management Science*. 2025;81(9):5260–5269. DOI: 10.1002/PS.8880
- [46] Gurusamy D, Mogilicherla K, Palli SR. Chitosan nanoparticles help double-stranded RNA escape from endosomes and improve RNA interference in the fall armyworm, *Spodoptera frugiperda*. *Archives of Insect Biochemistry and Physiology*. 2020;104(4):e21677. DOI: 10.1002/ARCH.21677
- [47] Zeng Y, et al. Polysaccharide-based nanomedicines for cancer immunotherapy: A review. *Bioactive Materials*. 2021;6(10):3358–3382. DOI: 10.1016/j.carbpol.2012.07.065
- [48] Hou T, et al. Biomedical applications of chitosan-coated phyto-genic silver nanoparticles: An alternative drug to foodborne pathogens. *International Journal of Biological Macromolecules*. 2024;280:135590
- [49] Alamgir ANM. Classification of Drugs, Nutraceuticals, Functional Food, and Cosmeceuticals; Proteins, Peptides, and Enzymes as Drugs. In Alamgir ANM, editor. *Therapeutic Use of Medicinal Plants and Their Extracts: Volume 1: Pharmacognosy*. Cham: Springer International Publishing; 2017:125–175. DOI: 10.1007/978-3-319-63862-1_5
- [50] Egerton S, et al. Replacing fishmeal with plant protein in Atlantic salmon (*Salmo salar*) diets by supplementation with fish protein hydrolysate. *Scientific Reports*. 2020;10(1):4194. DOI: 10.1038/S41598-020-60325-7
- [51] Patel R, Rajaraman TS, Rana PH, Ambegaonkar NJ, Patel S. A review on techno-economic analysis of lignocellulosic biorefinery producing biofuels and high-value products.

Results in Chemistry. 2025;**13**:102052.
 DOI: 10.1016/J.RECHEM.2025.102052

[52] Zhao Y, et al. A frustrating problem: Accelerated blood clearance of PEGylated solid lipid nanoparticles following subcutaneous injection in rats. *European Journal of Pharmaceutics and Biopharmaceutics*. 2012;**81**(3):506–513. DOI: 10.1016/j.ejpb.2012.04.023

[53] Dontsova TA, et al. Directional control of the structural adsorption properties of clays by magnetite modification. *Journal of Nanomaterials*. 2018;**2018**(1):6573016. DOI: 10.1155/2018/6573016

[54] Balci E, Rosales E, Pazos M, Sofuoglu A, Sanromán MA. Immobilization of esterase from *Bacillus subtilis* on Halloysite nanotubes and applications on dibutyl phthalate degradation. *Environmental Technology & Innovation*. 2023;**30**:103113. DOI: 10.1016/J.ETI.2023.103113

[55] Chauhan J, Sharma RK. Synbiotic formulations with microbial biofilm, animal derived (casein, collagen, chitosan) and plant derived (starch, cellulose, alginate) prebiotic polymers: A review. *International Journal of Biological Macromolecules*. 2023;**248**:125873. DOI: 10.1016/J.IJBIOMAC.2023.125873

[56] Chan CM, Lyons R, Dennis PG, Lant P, Pratt S, Laycock B. Effect of toxic phthalate-based plasticizer on the biodegradability of polyhydroxyalkanoate. *Environmental Science & Technology*. 2022;**56**(24):17732–17742. DOI: 10.1021/acs.est.2c06583

[57] Vijayaram S, Tsigkou K, Zuorro A, Sun YZ, Rabetafika H, Razafindralambo

H. Inorganic nanoparticles for use in aquaculture. *Reviews in Aquaculture*. 2023;**15**(4):1600–1617. DOI: 10.1111/RAQ.12803;PAGE:STRING:ARTICLE/CHAPTER

[58] Mahmudin L, et al. Silver nanoparticles-based localized surface plasmon resonance biosensor for *Escherichia coli* detection. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*. 2024;**311**:123985

[59] Usman M, et al. Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of the Total Environment*. 2020;**721**:137778

[60] Kah M, et al. Analysing the fate of nanopesticides in soil and the applicability of regulatory protocols using a polymer-based nanoformulation of atrazine. *Environmental Science and Pollution Research*. 2014;**21**(20):11699–11707. DOI: 10.1007/S11356-014-2523-6

[61] Fojtová D, et al. Nanoformulations can significantly affect pesticide degradation and uptake by earthworms and plants. *Environmental Chemistry*. 2019;**16**(6):470–481. DOI: 10.1071/EN19057

[62] Tejada M, Morillo E, Gómez I, Madrid F, Undabeytia T. Effect of controlled release formulations of diuron and alachlor herbicides on the biochemical activity of agricultural soils. *Journal of Hazardous Materials*. 2017;**322**:334–347. DOI: 10.1016/J.JHAZMAT.2016.10.002

[63] Ameen F, Alsamhary K, Alabdullatif JA, ALNadhari S. A review on metal-based nanoparticles and their toxicity to beneficial soil bacteria and fungi. *Ecotoxicology and*

Environmental Safety. 2021;**213**:112027. DOI: 10.1016/J.ECOENV.2021.112027

[64] Pascoli M, Jacques MT, Agarrayua DA, Avila DS, Lima R, Fraceto LF. Neem oil based nanopesticide as an environmentally-friendly formulation for applications in sustainable agriculture: An ecotoxicological perspective. *Science of the Total Environment*. 2019;**677**:57–67. DOI: 10.1016/J.SCITOTENV.2019.04.345

[65] Xu L, et al. Bactericidal dendritic polycation cloaked with stealth material via lipase-sensitive intersegment acquires neutral surface charge without losing membrane-disruptive activity. *ACS Applied Materials & Interfaces*. 2015;**7**(50):27602–27607. DOI: 10.1021/ACSAMI.5B09581

[66] Zhang B, Lu D, Wang DBR, Kok ZY, Chan-Park MB, Duan H. Enzyme-responsive polyion complex nanoparticles of cationic antimicrobials for activatable antibacterial therapy. *Advanced Functional Materials*. 2024;**34**(46):2407869. DOI: 10.1002/ADFM.202407869;WGROU:STRING: PUBLICATION

[67] Gottardo S, et al. Towards safe and sustainable innovation in nanotechnology: State-of-play for smart nanomaterials. *NanoImpact*. 2021;**21**:100297

[68] Luo J, et al. Self-assembled degradable nanogels provide foliar affinity and pinning for pesticide delivery by flexibility and adhesiveness adjustment. *ACS Nano*. 2021;**15**(9):14598–14609. DOI: 10.1021/ACSANO.1C04317

[69] Shan P, et al. Biodegradable and light-responsive polymeric nanoparticles for environmentally safe

herbicide delivery. *ACS Applied Materials & Interfaces*. 2022;**14**(38):43759–43770. DOI: 10.1021/ACSAMI.2C12106

[70] Kookana RS, et al. Nanopesticides: Guiding principles for regulatory evaluation of environmental risks. *Journal of Agricultural and Food Chemistry*. 2014;**62**(19):4227–4240. DOI: 10.1021/JF500232F

[71] Borm P, et al. Research strategies for safety evaluation of nanomaterials, part V: Role of dissolution in biological fate and effects of nanoscale particles. *Toxicological Sciences*. 2006;**90**(1): 23–32. DOI: 10.1093/TOXSCI/KFJ084

[72] Schoonjans R, et al. Regulatory safety assessment of nanoparticles for the food chain in Europe. *Trends in Food Science & Technology*. 2023;**134**:98–111

[73] Lamon L, Aschberger K, Asturiol D, Richarz A, Worth A. Grouping of nanomaterials to read-across hazard endpoints: A review. *Nanotoxicology*. 2019;**13**(1):100–118. DOI: 10.1080/17435390.2018.1506060;WGROU:STRIN G:PUBLICATION

[74] Hristozov D, et al. Frameworks and tools for risk assessment of manufactured nanomaterials. *Environment International*. 2016;**95**: 36–53

[75] Bergeson LL. Emerging nanomaterial governance systems: The state of play. *Molecular Imaging*. 2011;**10**(1):17–27. DOI: 10.2310/7290.2010.00052;WEBSITE:WEBSITE:SAGE; WGROU:STRING:PUBLICATION

[76] Su Y, et al. Cost-benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the

efficiency of nanoformulations for widescale adoption. *Nature Food*. 2022;**3**(12):1020–1030. DOI: 10.1038/s43016-022-00647-z

[77] Liu P, Yang M, Hermanowicz SW, Huang Y. Efficacy-associated cost analysis of copper-based nanopesticides for tomato disease control. *ACS Agricultural Science & Technology*. 2022;**2**(4):796–804. DOI: 10.1021/ACSAGSCITECH.2C00098

[78] Su T-R, Huang T-H, Kao C-T, Ng HY, Chiu Y-C, Hsu -T-T. The calcium channel affect osteogenic differentiation of mesenchymal stem cells on strontium-substituted calcium silicate/poly- ϵ -caprolactone scaffold. *Processes*. 2020;**8**(2):198. DOI: 10.3390/PR8020198

[79] Zhang XY, et al. Newly identified thermostable esterase from *Sulfobacillus acidophilus*: Properties and performance in phthalate ester degradation. *Applied and Environmental Microbiology*. 2014; **80**(22):6870–6878. DOI: 10.1128/AEM.02072-14

[80] Guo J, et al. Immobilized lignin peroxidase on Fe₃O₄@SiO₂@polydopamine nanoparticles for degradation of organic pollutants. *International Journal of Biological Macromolecules*. 2019;**138**:433–440

[81] Zhang L, et al. Glutathione S-transferase P influences redox homeostasis and response to drugs that induce the unfolded protein response in zebrafish. *Journal of Pharmacology and Experimental Therapeutics*. 2021;**377**(1):121–132. DOI: 10.1124/JPE.T.120.000417/-/DC1

[82] Jones J, Reneau P, Dos Santos JM. Metabolically healthy obese vs. Metabolic syndrome – The crosslink

between nutritional exposure to bisphenols and physical exercise. *Medical Hypotheses*. 2021;**149**:110542. DOI: 10.1016/J.MEHY.2021.110542

[83] Ji X, et al. Mesenchymal stem cell-loaded thermosensitive hydroxypropyl chitin hydrogel combined with a three-dimensional-printed poly(ϵ -caprolactone)/nano-hydroxyapatite scaffold to repair bone defects via osteogenesis, angiogenesis and immunomodulation. *Theranostics*. 2020;**10**(2):725. DOI: 10.7150/THNO.39167

[84] Alyassin Y, et al. Application of mesoporous silica nanoparticles as drug delivery carriers for chemotherapeutic agents. *Drug Discovery Today*. 2020; **25**(8):1513–1520. DOI: 10.1016/J.DRUDIS.2020.06.006

Chapter 3

Botanical Insecticides: Major Sources, and Chemical and Mechanistic Insights

Rizah Akbar, Hajra Bari, Tehreem Fatima, Ishfa Tahani and Naser A. Anjum

Abstract

The agriculture sector is one of the largest users of various synthetic (chemical) insecticides. However, extensive use of synthetic (chemical) insecticides has raised significant concerns, including environmental pollution, harm to non-target organisms, the development of pest resistance, and potential health risks to humans. Botanical insecticides, pest control products derived from plants, have become an important environmentally friendly alternative to synthetic (chemical) insecticides. In addition to their environmentally friendly nature, botanical insecticides offer benefits like low toxicity to non-target organisms, biodegradability, and reduced risk of pest resistance. Taking into account recent literature, this chapter aims to: (i) provide an overview of important insect pests and their impacts on crop health and productivity; (ii) highlight, with examples, the sources and chemical nature of major botanical insecticides (such as azadirachtin, pyrethrum, rotenone, allicin, and lemongrass essential oils); (iii) discuss important mechanistic insights (working principles) underlying botanical insecticides; and (iv) enlighten readers on the major challenges and future directions in this field.

Keywords: biotic stress, insects, pests, botanical insecticides, botanical insecticide chemistry, mechanism of action

1. Introduction

A diverse range of nutrients is required in the human body to function, grow, and maintain health. Macronutrients (e.g., carbohydrates, proteins, and fats) and micronutrients (e.g., vitamins and minerals) provide energy and the building blocks for tissues and are essential for various bodily processes. In addition, dietary fibers and bioactive compounds (phytochemicals) are endowed with antioxidant, anti-inflammatory, and cardioprotective properties that help prevent fatal diseases. As the foundational source of the global food system, plants (agriculture) provide most of the calories and a wide spectrum of nutrients required by humans for a healthy life. Hence, plants (agriculture) have become the indispensable foundation of human

nutrition and global food security. Humans have been very much dependent on plant-sourced foods. To this end, the optimal diet comprising whole foods, high fiber, low-fat, and over 90% plant (agriculture)-based diet was argued to have allowed humans to become the most developed species on planet Earth [1, 2].

Major constraints for plant-based food can be categorised into three important groups: *production and environmental constraints* (e.g., climate change and weather variability; resource scarcity and degradation; pests, weeds, and diseases; and input management), *economic and socio-economic constraints* (e.g., market volatility and access; financial limitations; labor and land issues; and lack of knowledge and information), and *infrastructure and supply chain constraints* (e.g., inadequate infrastructure; supply chain inefficiencies; and technological gaps). In particular, pests, weeds, and diseases pose a significant challenge to agriculture, causing an estimated 20–40% loss of global crop yields annually. These threats impact food security, increase production costs, and have environmental consequences through the use of control measures [3, 4].

2. Insect pests, impacts, and control measures

Insects, hexapod invertebrates of the class Insecta, are the largest group within the phylum Arthropoda. Most insects are either neutral or beneficial and provide vital ecosystem services such as pollination, nutrient cycling, or pest control. However, less than 1.0–3.0% of all insect species are actual pests. Major factors driving the process of insects becoming pests (insect pests) include habitat alteration, climate change, and loss of biodiversity. Common pests and damage types include: (i) sucking pests (e.g., aphids, whiteflies, thrips, mites, mealybugs, scale insects, which pierce and suck cell sap, causing yellowing, stunted growth, and virus transmission); (ii) chewing pests (e.g., caterpillars like cabbage loopers, armyworms, hornworms; leaf beetles, grasshoppers, which eat leaves, fruits, and flowers); and (iii) boring pests (e.g., fruit borers like fruit flies and mango seed weevils; stem borers like weevils and clearwing borers, which damage stems, fruits, and roots). Insect pests cause a wide range of impacts on plant health and productivity, which may include physical damage and defoliation, disruption of plant physiology, vectoring of plant pathogens, damage to roots and stems, and reduction in commercial and nutritional quality [5]. By doing these, insect pests damage about 10–28% of global crops annually. In specific regions like India, insect pest-accrued crop loss (reaching up to 18–20%) is driven by practices that favour pests and changing climate [6–8].

Given the insect pests as a significant threat to global food security (causing substantial crop health impacts and losses), there is an urgent need for effective and sustainable strategies for managing the insect pests. Unfortunately, most current insect pest management strategies are not sustainable and largely rely on conventional chemical pesticides. These conventional chemical pesticides have led to numerous environmental, health, and economic problems that compromise long-term effectiveness and sustainability. The list of important impacts on agriculture and the environment includes soil degradation, water contamination, biodiversity loss, and pest resistance [3, 4, 9, 10].

Interestingly, as a holistic framework, integrated pest management (IPM) has emerged to achieve sustainable agricultural intensification. IPM combines various

methods (cultural, biological, physical, chemical) to minimize pesticide reliance, boost crop health, protect the environment, and ensure long-term economic viability, focusing on prevention and ecological balance rather than solely chemical control. Moreover, IPM promotes sustainable intensification by reducing chemical use, acting as an ecological approach, emphasising the belief that healthy soils produce healthy crops, ensuring economic efficiency, and integrating technology and monitoring [11, 12].

3. Botanical insecticides

Derived from plants, botanical insecticides are bioinsecticides, which stand second to none among the sustainable insect pest management strategies. Other key bioinsecticide types and underlying mechanisms include microbial pesticides (where bacteria, like *Bacillus thuringiensis*; fungi, like *Beauveria bassiana* and *Metarhizium anisopliae*; viruses, like Baculoviruses; and nematodes, like *Steinernema* and *Heterorhabditis*, are employed to infect, paralyze, or kill selected insect pests) and plant-incorporated protectants (PIPs) (where genetically modified plants produce their own insecticides, e.g., *Bacillus thuringiensis*/ *Bt*-toxins) [13, 14]. Effort was made hereunder to overview azadirachtin, pyrethrum, rotenone, allicin, and lemongrass essential oils, and also to enlighten their major sources, important insights into their chemistry, and mode(s) of action against the insect pests.

3.1 Azadirachtin

3.1.1 Background

Azadirachtin (a complex tetranortriterpenoid limonoid) is one of the most important botanical pesticides in modern agriculture. It acts as the foundation of IPM tactics and organic agricultural systems worldwide. Azadirachtin exhibits excellent selectivity for arthropod pests and low toxicity to vertebrates, nontarget species, and broader agroecosystems. Currently registered for agricultural use in more than 40 countries, azadirachtin formulations have received widespread international recognition [15]. In contrast to synthetic pesticides, azadirachtin is remarkably biodegradable. The breakdown products of azadirachtin are effective against more than 550 pest species from orders including Coleoptera, Hemiptera, Diptera, Orthoptera, and Isoptera. Additionally, the azadirachtin-breakdown products also improve soil as natural fertilizers [16]. Furthermore, *A. indica*-based formulations (such as azadirachtin) avoid the biotoxicity and pollution problems resulting from conventional pesticide use [16, 17].

3.1.2 Source

Neem (*Azadirachta indica* A. Juss) (family – Meliaceae) is the main source of azadirachtin compounds. Native to India and Myanmar, *A. indica* grows well in the tropical and subtropical climates of countries in southern Asia, Africa, and South America [15, 18]. Mature fruits of *A. indica* usually contain between 0.3% and 1% azadirachtin on a dry weight basis. However, azadirachtin content in leaves and

branches remains relatively low. *A. indica* is known for its various therapeutic roles and the significance of its active constituents in disease prevention and treatment [19]. *A. indica* tree parts possess over 300 distinct phytochemicals. Interestingly, more than 130 of these phytochemicals are limonoid-type triterpenoids, which have strong insecticidal and therapeutic effects. Apart from azadirachtin, notable neem limonoids include nimbolide, salanin, nimbin, deacetylnimbin, mahmoodin, epoxy-azadiradione, deacetylgedunin, and gedunin [20–22].

3.1.3 Chemical nature

Azadirachtin A is the most active component, accounting for 72–90% of the overall biological activity [20]. Notably, azadirachtin has 13 structurally similar variations, known as A, B, D, E, F, G, H, I, K, M, N, O, and Q, with azadirachtin A and B accounting for 99% of the total azadirachtin content in *A. indica* seeds [15]. About 90% of the fixed oil from *A. indica* seed kernels is composed primarily of triglycerides. On the other hand, about 2% of the bitter yellow oil is constituted by nimbidin, nimbrin, nimbinin, nimbidol, and other similar limonoids [20].

3.1.4 Mechanistic insights (mode of action)

Multifaceted modes of action mediate the insecticidal actions of azadirachtin. The modes of action of azadirachtin include (i) feeding deterrence and chemoreceptory effects; (ii) neuroendocrine disruption and growth inhibition; and (iii) reproductive and cellular effects. Acting as a feeding deterrent and chemoreception agent, azadirachtin directly interacts with the insect's gustatory (taste) receptors, stimulates bitter-sensitive cells, and inhibits sugar receptors. Azadirachtin causes insects to prefer starvation over consuming treated food by creating an aversive taste memory. Moreover, azadirachtin also leads to starvation and eventual death by reducing the food intake rate and the efficiency of converting ingested food into body mass. Azadirachtin-mediated neuroendocrine disruption and growth inhibition involve hormone blockage, molting interference, and mortality. On the other hand, the reproductive and cellular effects of azadirachtin involve reproductive impairment, behavioural changes, and severe cellular damage [16, 23].

3.2 Pyrethrum

3.2.1 Background

Pyrethrum is a powerful, fast-acting natural insecticide derived from crushed *Chrysanthemum* (or *Tanacetum cinerariifolium*) flowers. Pyrethrum plays a significant role in agriculture. It has been a cornerstone for organic growers and is approved for controlling pests on fruits, vegetables, and other crops. As a broad-spectrum insecticide, it is effective against many pests, such as aphids, mites, whiteflies, caterpillars, and beetles. This botanical insecticide helps farmers adopt sustainable practices by offering natural pest control without persistent chemical buildup. In addition, pyrethrum exhibits low mammalian toxicity and is generally safer for humans and beneficial insects (like bees) [24, 25].

3.2.2 Source

Key sources of pyrethrum include the plants of *Chrysanthemum cinerariifolium* (or *Tanacetum cinerariifolium*). However, *C. coccineum* and *C. marshalli* are other chrysanthemum species known to contribute to pyrethrum production. Major regions known to cultivate *C. cinerariifolium* (or *T. cinerariifolium*), *C. coccineum*, and *C. marshalli*, and produce pyrethrum globally include East Africa (Kenya, Tanzania, and Rwanda), Tasmania (Australia), and Southern China [24].

3.2.3 Chemical nature

Pyrethrum is a mixture with the chemical formula $C_{43}H_{56}O_8$, and each of the six active compounds (pyrethrins) in it has a cyclopropane ring core responsible for their insecticidal activity. The six active insecticidal constituents are: Pyrethrin I, Pyrethrin II, Cinerin I, Cinerin II, Jasmolin I, and Jasmolin II. Pyrethrum is poorly soluble in water and undergoes rapid degradation upon exposure to light, heat, or air, leading to low environmental persistence. There are three esters of chrysanthemic acid and three esters of pyrethric acid present in pyrethrum. Among the six esters, Pyrethrin I and Pyrethrin II incorporate the alcohol pyrethrolone, which is responsible for most of the insecticidal activity [26–29].

3.2.4 Mechanistic insights (mode of action)

Mechanism of action of pyrethrum includes alteration in the activity of voltage-gated sodium ion channels in the insect's nervous system, which, in turn, leads to hyperexcitation, paralysis, and death (a knockdown effect). Pyrethrins interfere with the process of voltage-gated sodium ion channels by slowing channel closure, causing persistent depolarisation, inducing repetitive firing (of nerve impulses), and creating conduction blockade (of the nervous system) [30].

3.3 Rotenone

3.3.1 Background

Rotenone is a natural insecticide, acaricide, and piscicide derived from plant roots (such as *Derris* and *Lonchocarpus*). It is widely used to control pests on crops, animals, and in water. In agriculture, the uses of rotenone include pest control, as it kills pests like aphids, beetles, cabbage worms, and mites through contact and stomach action, with quick knockdown. Key characteristics include its natural origin and fast degradation. Major concerns include non-selectivity (because rotenone also kills beneficial insects, pollinators, and pests alike) and toxicity (as rotenone is toxic in higher doses to humans, animals, and fish) [28, 31].

3.3.2 Sources

Rotenone is found naturally in the roots, stems, and leaves of various leguminous plant species from the Fabaceae (Leguminosae) family, including *Derris*,

Lonchocarpus, Tephrosia, and Amorpha [31, 32]. Among these genera, Derris species are the most commercially important sources worldwide [32, 33].

3.3.3 Chemical nature

Rotenone possesses a unique isoflavonoid nucleus (which has an isoprene moiety (C_5H_8) precisely at the C-8 position on ring A), which gives it its distinct three-dimensional geometry and remarkable biological activity profile [32, 34]. The isoflavonoid framework enables rotenone to selectively target mitochondria and engage in unique metabolic interactions among insecticides derived from plants [31, 32].

3.3.4 Mechanistic insights (mode of action)

Rotenone insecticide works by blocking Complex I (NADH dehydrogenase) in the mitochondrial electron transport chain, halting ATP (energy) production, and causing cell death, paralysis, and ultimately death in insects by disrupting cellular respiration and creating damaging reactive oxygen species (ROS). In other words, rotenone-mediated control of insect pests involves inhibition of electron transport, blockage of ATP synthesis, onset of oxidative stress, and cellular damage and death [35, 36].

3.4 Allicin

3.4.1 Background

Continued use of synthetic insecticides and fumigants has resulted in a number of issues, such as insecticide and fumigant resistance and chemical insecticide residues in food (Bilgin et al. [37]). Therefore, there is an urgency to find alternative approaches for combating insects and pests with reduced environmental and mammalian impacts. For centuries, garlic has been used as a medicinal plant, especially for its potent antimicrobial activity. Several studies have also demonstrated the strong insecticidal activity of garlic essential oil [38, 39]. Various commercial formulations of allicin (the main bioactive organosulphur compound synthesised in *Allium* sp.), such as emulsifiable concentrates, wettable powders, microencapsulated forms, and nanoemulsions, are used in various countries of Asia (India, China, Japan, Indonesia, Philippines, and Vietnam), Africa (Kenya, Tanzania, Uganda), Europe (United Kingdom, France, Italy), and North America (USA, Canada). They are effective against a wide range of insects, such as Dipterans, Lepidopterans, Hemipterans, Coleopterans, and Orthopterans, mainly by contact toxicity, repellence, and feeding deterrence.

3.4.2 Sources

Garlic (*Allium sativum* L.) is a bulbous plant of the Liliaceae family, native to Central Asia, but it is also found in several countries around the world. It serves as the chief and most effective source of allicin.

Allicin ($C_6H_{10}S_2$) is a transient, reactive, and sulphur containing volatile compound, also known as allyl 2 – propenethiosulfinate, diallyl thiosulfinate, or S – allyl cysteine sulfoxide. From one clove of fresh garlic, 4–5 mg of allicin can be obtained, which is

easily detected due to its pungent odour [37]. Other plants from the *Allium* genus, such as *Allium ursinum* (wild garlic), *Allium porrum* (leeks), and *Allium cepa* (onion), also produce trace amounts of allicin, but their yields are low.

3.4.3 Chemical nature

Allicin is a colourless oil with low water solubility. It is unstable and breaks down quickly, especially with heat or moisture. The formula of allicin is $C_6H_{10}OS_2$. It's a thiosulfinate (R-S(O)-S-R) that has two allyl groups, containing two sulphur atoms and one oxygen atom. In fresh garlic, allicin is the most abundant thiosulfinate and constitutes about 70% (w/w) of the total thiosulfonates. When garlic tissue is damaged, the enzyme alliinase converts alliin (S-allyl-L-cysteine sulfoxide) into allyl sulfenic acid, which then condenses to form allicin [40].

3.4.4 Mechanistic insights (mode of action)

Allicin attacks pests by chemically interfering with their fundamental life processes through thiol modification and oxidative damage, disrupting enzymes and cellular structures necessary for survival. In other words, key modes of action of allicin include thiol-binding and enzyme inhibition, oxidative stress induction, and membrane disruption. Allicin readily reacts with free thiol (sulfhydryl, -SH) groups in proteins and cofactors (like glutathione). This modification inactivates critical enzymes, such as those involved in energy production (acetyl-CoA), maintaining cell health (thioredoxin reductase), and metabolism (alcohol dehydrogenase), leading to cell death. Allicin causes oxidative stress by generating ROS within target cells, which cause widespread damage to DNA, proteins, and cell membranes, disrupting cellular function. Allicin disrupts membranes, reaches intracellular targets, and enhances its overall toxicity [41, 42].

3.5 Lemongrass essential oil

3.5.1 Background

Essential oils are plant-derived volatile compounds. Essential oils widely used as botanical insecticides are obtained from a wide range of plants (and/or from their parts), for example, peppermint, clove, citronella, eucalyptus, lavender, rosemary, neem, and lemongrass. These plant-derived volatile compounds are used as eco-friendly pesticides, acting as repellents, fumigants, or toxins by disrupting insect nervous systems, growth, or respiration, offering safer alternatives to synthetics. At the same time, plant-derived volatile compounds are safe for humans and the environment and are important 'green' solutions for agriculture. This is because plant-derived volatile compounds (essential oils) contain terpenes and phenolics that target multiple insect mechanisms, making resistance less likely, and are biodegradable with low mammalian toxicity [43].

3.5.2 Sources

Lemongrass (*Cymbopogon citratus*, family Poaceae), indigenous to India and Sri Lanka, is recognized for its properties derived from various parts. The oil in lemongrass is sherry-coloured, with a flavour and a lemon-scented aroma. The

bioactive components, comprising compounds, terpenoids, phenolics, proteinase inhibitors, and growth inhibitors, act primarily as repellents, toxins, feeding deterrents, and growth modulators, particularly targeting insects, mosquitoes, and dipteran flies. Lemongrass leaves hold their oil, comprising approximately 1–2% of dry weight, within specialized oil cells in the parenchyma tissues [44].

3.5.3 Chemical nature

The primary component is citral, which is made up of two isomers: geranial (citral A) (E-isomer, usually dominant: 0.99–48.14%) and citral B (Z-isomer: 0–38.32%). Alcohols, terpenes, ketones, aldehydes, esters, along with phytochemicals such as nerol, geraniol, citronellal, myrcene, and flavonoids (like luteolin, quercetin, and kaempferol), are additional bioactive substances.

3.5.4 Mechanistic insights (mode of action)

Major modes of action of lemongrass essential oils include (i) respiratory and locomotor inhibition; (ii) disruption of detoxification and antioxidant systems; and (iii) physical and developmental damage. These multi-faceted mechanisms make lemongrass essential oils a potential natural alternative to synthetic pesticides and preservatives. Lemongrass essential oils can decrease the respiration rate and impair the movement of insects, contributing to their death. Lemongrass essential oils can inhibit key detoxification enzymes, such as carboxylesterase and glutathione S-transferase, and induce oxidative stress by affecting antioxidant enzyme activity. Lemongrass essential oils can also cause histopathological effects in the midgut of insects and exhibit significant cytotoxic activity that leads to mortality and can impact normal development (e.g., larval duration) of pests. Moreover, the hydrophobic components of the lemongrass essential oils interact with the lipids in cell membranes, increasing permeability and ultimately causing cell death in microbes [45] (Fiaz et al., 2019, [46]).

4. Conclusions, challenges, and prospects

Azadirachtin is obtained from the seeds of *A. indica*. It acts as an antifeedant (stopping feeding), insect growth regulator (disrupting molting and development), and repellent (preventing pests from reaching adulthood and reproducing). It is effective against over 200 insect species, including thrips, aphids, whiteflies, caterpillars, and mites. Azadirachtin is eco-friendly; it is biodegradable, non-toxic to humans and animals, and safe for beneficial insects and pollinators, making it suitable for organic farming. Derived from the dried flowers of chrysanthemum plants (like *Chrysanthemum cinerariifolium*, which contains pyrethrins), pyrethrum is a natural insecticide that paralyzes and kills insects by attacking their nervous systems. Rotenone is a naturally derived, colourless, crystalline compound from certain plants (like jicama and Derris) and is used as a broad-spectrum insecticide. Its mode of action includes inhibition of mitochondrial respiration (Complex I), thereby stopping energy production. Allicin is a natural, sulphur-containing compound from *Allium sativum*. Allicin-mediated control of insect pests involves mechanisms such as disrupting cell membranes and targeting proteins.

Obtained from lemongrass, lemongrass oil is rich in compounds like citral. Acting as an eco-friendly repellent and killer for various insects, the mode of action of citral involves disruption of the nervous systems and digestion of insect pests.

Major challenges for botanical insecticides can be grouped into two categories, namely scientific and technical challenges (e.g., variability, stability and efficacy, formulation, and sourcing and production) and economic and regulatory hurdles (e.g., cost-effectiveness, regulatory frameworks, and lack of data). Botanical insecticides can become a vital part of sustainable agriculture and food security by increasing research into new plant sources, integrating them with digital farming, and implementing supportive policies to boost commercialisation. The stability and potency of botanical insecticides may be enhanced by focusing on advanced formulations (like nano-delivery systems) and biotechnological methods. More research on environmental impact, long-term safety, and mechanisms of action is needed. In addition, the use of botanical insecticides can further benefit from the development of supportive policies and regulatory frameworks.

Author details

Rizah Akbar^{1#}, Hajra Bari^{1#}, Tehreem Fatima^{1#}, Ishfa Tahani[#] and Naser A. Anjum^{*}

1 Department of Botany Aligarh Muslim University, Aligarh, India

Contributed equally to this work.

*Address all correspondence to: naanjum1@myamu.ac.in

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Dwivedi SL, Van Bueren ETL, Ceccarelli S, Grando S, Upadhyaya HD, Ortiz R. Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends in Plant Science*. 2017;22(10):842–856
- [2] Goldfarb G, Sela Y. The ideal diet for humans to sustainably feed the growing population – review, meta-analyses, and policies for change. *F1000Research*. 2023;10:1135
- [3] Kumar S, Sharma A, Samal RR. Management of Agricultural Pests: Strategies and Constraints. In Kumar S, editor. *Insecticides in Pest Control - Impact, Challenges and Strategies*. London (United Kingdom): IntechOpen; 2024. p. 3–19. DOI: 10.5772/intechopen.1006075
- [4] Umar OB, Ranti LA, Abdulbaki AS, Bola AUL, Abdulhamid AK, Biola MR, Victor KO. Stresses in plants: Biotic and abiotic. In Ansari MR, editor. *Current Trends in Wheat Research*. London (United Kingdom): IntechOpen; 2021. p. 139–146. DOI: 10.5772/intechopen.100501
- [5] Ouaraous M, El Fakhouri K, Taarji N, Baouchi A, Amri M, Ramdani C, . . . Sobeh M. Impact of field insect pests on seed and nutritional quality of some important crops: A comprehensive review. *ACS Omega*. 2025;10(9): 8779–8792
- [6] Chinnasamy S, Baskar R. Investigations on identification of pests in horticultural crops under greenhouse conditions. *Horticultural Science*. 2024;51(2):75–84
- [7] Jankielsohn A. The importance of insects in agricultural ecosystems. *Advances in Entomology*. 2018;6(2): 62–73
- [8] Mukhtar Y, Shankar U, Wazir ZA. Prospects and challenges of emerging insect pest problems vis-à-vis climate change. *Indian Journal of Ecology*. 2023;50(4):1096–1103
- [9] Dhuldhaj UP, Singh R, Vks S. Pesticide contamination in agro-ecosystems: Toxicity, impacts, and bio-based management strategies. *Environmental Science and Pollution Research*. 2023;30(4):9243–9270
- [10] Ayotunde AA, Thota S. Integrated pests management and food security: A mathematical analysis. *Computational Methods for Differential Equations*. 2025;13(2):524–537
- [11] Tiwari AK. IPM essentials: Combining biology, ecology, and agriculture for sustainable pest control. *Journal of Advances in Biology & Biotechnology*. 2024;27(2):39–47
- [12] Zhou W, Arcot Y, Medina RF, Bernal J, Cisneros-Zevallos L, Akbulut MES. Integrated pest management: An update on the sustainability approach to crop protection. *ACS Omega*. 2024;9(40):41130–41147
- [13] Chaudhary S. Progress on *Azadirachta indica* Based Biopesticides in Replacing Synthetic Toxic Pesticides. *Frontiers in Plant Science*. 2017;8(8):610
- [14] Mawcha KT, Kinyanjui G, Simiyu SW, Babalola OO, Ndolo DO. Biopesticides for sustainable agriculture: A review of their role in integrated pest management. In Kumar S, editor.

Insecticides in Pest Control - Impact, Challenges and Strategies. London (United Kingdom): IntechOpen; 2024. p. 189–206. DOI: 10.5772/intechopen.1006277

[15] Su X, Liang Z, Xue Q, Liu J, Hao X, Wang C. A comprehensive review of azadirachtin: Physicochemical properties, bioactivities, production, and biosynthesis. *Acupuncture and Herbal Medicine*. 2023;3(4):256–270

[16] Kilani-Morakchi S, Morakchi-Goudjil H, Sifi K. Azadirachtin-based insecticide: Overview, risk assessments, and future directions. *Frontiers in Agronomy*. 2021;3:676208

[17] Damalas CA, Koutroubas SD. Current status and recent developments in biopesticide use. *Agriculture*. 2018;8(1):13

[18] Kumar D, Rahal A, Malik JK. Neem extract. In: Gupta RC ed. *Nutraceuticals*. Boston (United States): Academic Press; 2016. p. 585–597

[19] Alzohairy MA. Therapeutics role of *Azadirachta indica* (Neem) and their active constituents in diseases prevention and treatment. *Evidence-Based Complementary and Alternative Medicine*. 2016;2016:7382506

[20] Boadu KO, Tulashie SK, Anang MA, Kpan JD. Production of natural insecticide from Neem leaves (*Azadirachta indica*), 2011

[21] Chen J, Fan X, Zhu J, Song L, Li Z, Lin F, et al. Limonoids from seeds of *Azadirachta indica* A. Juss. and their cytotoxic activity. *Acta Pharmaceutica Sinica B* 2018;8:639–644

[22] Gupta SC, Prasad S, Tyagi AK, Kunnumakkara A, BB A. Neem

(*Azadirachta indica*): An Indian traditional panacea with modern molecular basis. *Phytomedicine*. 2017;34:14–20

[23] Singh G, Chandi AK, Kaur A. Lethal, sublethal and antifeedant effects of azadirachtin on some major insect-pests: A review. *Agricultural Reviews*. 2025;1–8. DOI: 10.18805/ag.R-2692

[24] Matsuo N. Discovery and development of pyrethroid insecticides. *Proceedings of the Japan Academy, Series B*. 2019;95(7):378–400

[25] Sun W, Shahrajabian MH, Cheng Q. Pyrethrum an organic and natural pesticide. *Journal of Biological and Environmental Sciences*. 2020;14(40):41–44

[26] Casida JE, Quistad GB. *Pyrethrum Flowers: Production, Chemistry, Toxicology and Uses*. Oxford (United Kingdom): Oxford University Press; 1995

[27] Dively GP, Patton T, Barranco L, Kulhanek K. Comparative efficacy of common active ingredients in organic insecticides against difficult to control insect pests. *Insects*. 2020;11(9):614

[28] Isman MB. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*. 2006;51:45–66

[29] Kojima T, Yamato S, Kawamura S. Natural and synthetic pyrethrins act as feeding deterrents against the black blowfly. *Phormia Regina* (Meigen). *Insects*. 2022;13(8):678

[30] Hodoşan C, Gîrd CE, Ghica MV, Dinu-Pîrvu CE, Nistor L, Bărbuică IS, et

- al Pyrethrins and pyrethroids: A comprehensive review of natural occurring compounds and their synthetic derivatives. *Plants*. 2023;**12**:4022
- [31] Gonzalez-Coloma A, Reina M, Diaz CE, Fraga BM. Natural product-based biopesticides for insect control. In: Mander LN, Liu H-W eds. *Comprehensive Natural Products II*. Amsterdam (The Netherlands): Elsevier; 2010. p. 237–263
- [32] Zubairi SI, Sarmidi MR, Aziz RA. A study of rotenone from *Derris* roots of varies location, plant parts and types of solvent used. *Advances in Environmental Biology*. 2014;**8**(2): 445–449
- [33] Zubairi SI, Othman ZS, Sarmidi MR, Aziz RA. Environmental friendly bio-pesticide rotenone extracted from *Derris* sp.: A review on the extraction method, toxicity and field effectiveness. *Jurnal Teknologi*. 2016;**78**(8):47–69
- [34] Sae-Yun A, Ovatlarnporn C, Itharat A, Wiwattanapatapee R. Extraction of rotenone from *Derris elliptica* and *Derris malaccensis* by pressurized liquid extraction compared with maceration. *Journal of Chromatography A*. 2006;**1125**(2): 172–176
- [35] Mandal I. Chapter-2 Botanicals: As Alternate to Synthetic Insecticides for Insects Pest Management. *ENTOMOLOGY*. 2024;**6**:33–39
- [36] Shivanandappa T, Rajashekar Y. Mode of action of plant-derived natural insecticides. In: Singh D, ed. *Advances in Plant Biopesticides*. New Delhi, India: Springer; 2014. p. 323–345
- [37] Horev-Azaria L, Eliav S, Izigov N, et al. Allicin up-regulates cellular glutathione level in vascular endothelial cells. *European Journal of Nutrition*. 2009;**48**:67–74
- [38] Huang Y, Chen SX, Ho SH. Bioactivities of methyl allyl disulfide and diallyl trisulfide from essential oil of garlic to two species of stored-product pests, *Sitophilus zeamais* (Coleoptera: Curculionidae) and *Tribolium castaneum* (Coleoptera: Tenebrionidae). *Journal of Economic Entomology*. 2000;**93**(2):537–543
- [39] Park I-K, Choi K-S, Kim D-H, Choi I-H, Kim L-S, Bak W-C, Choi J-W, Shin S-C. Fumigant activity of plant essential oils and components from horseradish (*Armoracia rusticana*), anise (*Pimpinella anisum*) and garlic (*Allium sativum*) oils against *Lycoriella ingenua* (Diptera: Sciaridae). *Pest Management Science*. 2006;**62**(8): 723–728
- [40] Rybak ME, Calvey EM, Harnly JM. Quantitative determination of allicin in garlic: supercritical fluid extraction and standard addition of alliin. *Journal of Agricultural and Food Chemistry*. 2004;**52**(4):682–687
- [41] Borlinghaus J, Albrecht F, Gruhlke MC, Nwachukwu ID, Slusarenko AJ. Allicin: Chemistry and biological properties. *Molecules*. 2014;**19**(8):12591–12618
- [42] Gruhlke MCH, Portz D, Stitz M, Anwar A, Schneider T, Jacob C, et al. Allicin disrupts the cell's electrochemical potential and induces apoptosis in yeast. *Free Radical Biology and Medicine* 2010;**49**:1916–1924
- [43] Ayllón-Gutiérrez R, Díaz-Rubio L, Montaña-Soto M, Haro-Vázquez MDP,

Córdova-Guerrero I. Applications of plant essential oils in pest control and their encapsulation for controlled release: A review. *Agriculture*. 2024;**14**(10):1766

[44] Skaria BP, Joy PP, Mathew G, Mathew S, Joseph A. Lemongrass. In Peter KV, editor. *Handbook of Herbs and Spices*. Vol. **228**. 2nd ed. LTD, Abington Hall Abington, Cambridge CB1 6AH, Cambs, England: Woodhead Publ; 2012. p. 348–370

[45] Martínez LC, Plata-Rueda A, Colares HC, Campos JM, Dos Santos MH, et al Toxic effects of two essential oils and their constituents on the mealworm beetle, *Tenebrio molitor*. *Bulletin of Entomological Research*. 2018;**108**:716–725

[46] Plata-Rueda A, Rolim GDS, Wilcken CF, Zanuncio JC, Serrão JE, Martínez LC. Acute toxicity and sublethal effects of lemongrass essential oil and their components against the granary weevil, *Sitophilus granarius*. *Insects*. 2020;**11**(6):379

Perspective Chapter: Role of Insecticides in Biological Control Agents and Their Impacts

Arbaz Khan, Muhammad Yaseen, Sehrish Zafar and Sarfraz Ali Shad

Abstract

The agriculture sector plays a pivotal role in ensuring food security and contributing to economic stability. Despite its advantages, the widespread use of synthetic pesticides for pest control poses significant threats to human health, environmental quality, and biological control agents. This chapter highlights the dual nature of pesticides, focusing on their benefits in enhancing crop yields and their adverse impacts on non-target species. Their harmful effects on natural and artificial biological control agents exacerbate pest resistance and resurgence, challenging sustainable pest management. To mitigate these issues, this article emphasizes the need for selective pesticide use, integration of biological resistance in control agents, and advanced studies on pesticide effects at molecular and behavioral levels. Future directions advocate for innovative strategies to balance agricultural productivity with environmental and public health conservation.

Keywords: biological control agent, pesticides impacts, resistant bio control, IPM system, resistance threat

1. Introduction

The agriculture sector plays an important role in the world economy as it contributes 4.13% to GDP (Gross Domestic Product) and provides employment to 37.4% of people, which is important for food security and for providing raw materials to the industrial sector [1]. As the population increases continuously, it may reach up to 9.8 billion in 2050 and 11.2 billion in 2100 [2], which leads to industrialization. In South Asia, the population has increased continuously and developed pressure on the same resources; that's why, after the Green Revolution, the usage of pesticides increased. The increase in pesticide usage led to a rise in the production of cereal crops; wheat production increased six-fold in India since (1961–98), and rice yield doubled in Sri Lanka [3]. But pesticides also have a dark side; these pesticides, like organophosphates (OPs), methyl parathion, DDT, DDE, and HCH, cause different diseases and the deaths of many people around the world.

According to the World Health Organization (WHO), the term “pesticides” is considered hypothetical toxic chemical compounds that help us control insect pests, rodents, bacteria, fungi, acarids, and weeds [4]. Besides agricultural ecosystems, pesticides are also used in the domain of public health protection, such as mosquito control [5]. In the developing world (underdeveloped countries), farmers mostly rely on chemical control as it provides immediate control without any hard effort [6]. Moreover, it is comparatively cheap and easy to use for controlling pests, but the dark side is that it develops resistance in pests [7] and causes various severe diseases in human beings and other terrestrial and aquatic organisms [8]. Chemical control mostly disturbs both biotic and abiotic components of the community as it accumulates in the food chain [9] and also damages non-target biological control (BC) agents [10, 11].

For the first time in history, Rachel Carson efficiently raised her voice against the excessive use of pesticides in her book “**Silent Spring**” [12]. Since then, many articles have been published describing how sole dependence on pesticides leads to a poisonous world. A recent study revealed that the harmful chemicals in pesticides cause genetic disorders, cancer, respiratory problems, and also disturb human reproduction [13].

Globally, 2.5 million tons of pesticides are applied to crops; of these, only 0.1% are applied efficiently to the target, while the remaining 99.9% are absorbed into the environment, where they contaminate soil and water and have negative impacts on BC agents [14]. In developing countries, only 25% of pesticides are used, but they face an almost 99% death ratio [15] due to poor and unsafe use of pesticides, lack of proper educational systems, and inefficient hospital structures [16]. Pesticides are broadly divided into two groups: old chemistry and new chemistry groups. Old chemistry includes organochlorines (OCs), OPs, carbamates, and pyrethroids, while new chemistry includes all remaining groups except the above four, for example, phenylamides, phenoxyalkanoates, triazines, benzoic acid, phthalimides, and dipyrids, etc. [4]. The three main categories are used for pesticides depending on pesticide utility, entrance to target species, and entity. Furthermore, the WHO classified them into four main groups: (a) considerably harmful, (b) moderately dangerous, (c) greatly hazardous, and (d) extremely hazardous [17].

2. What are BC agents and why are they important?

BC agents are beneficial insects that feed on harmful insects (pests). They actively feed on pest species and, as a result, pest populations decrease. The importance of BC has increased in the past three decades because of resistance development in pests. The term “biological control” was first used by Smith and Taylor [18] for exotic insect species used in the suppression of harmful pests. The term “biological control agents” is broad, but more precisely, it includes predators, parasites, parasitoids, antagonists, and, for weed control, phytophages. Their main targets include different pests (anything that harms humans and competes with their economic interests), plant pathogens, invertebrates that feed on plants, and different types of vectors that spread diseases.

Before its proper definition and application, BC was used centuries ago. At that time, when BC was unknown, humans protected their grains from rodents by keeping cats. However, the discovery of microbes in the nineteenth century led to further research (mostly unsuccessful) as the life cycles of different insects began to be understood. The first publicized and highly successful introduction of the vedalia

beetle (*Rodolia cardinalis*) from Australia into California in 1888 to control the disastrous pest cotton cushion scale (*Icerya purchasi*) was formally considered the beginning of traditional BC as a discipline [19].

The successful control of *I. purchasi* generated excitement and developed interest worldwide; as a result, different BC agents, like ladybird beetles, were reared and dispatched from continent to continent [20]. From the USA, the first insect parasitoid was introduced into Italy in 1906 for the control of mulberry scale (*Pseudaulacaspis pentagona*) [21]. During the initial periods, poor success rates led to the realization that a more accurate, scientific approach, including taxonomy, ecology, genetics, and biology, was needed for studying populations of natural enemies. After World War II, exploration was limited because of the discovery of the most powerful organic insecticides. However, soon these chemicals became ineffective as insects developed resistance after repeated applications. Subsequently, the harmful impacts of OCs on the environment were exposed by Carson [12], and the cost of pesticides rose to its peak after the oil crisis of 1973. The combination of these factors led toward a more scientific approach to pest control, including the integrated pest management concept, as it reduced pest resurgence.

3. History of insecticides use

Ancient people used botanical substance preparations as insecticides. For example, 1.5% pyrethrins (active ingredients of insecticide) found in the flowers of Dalmatian pyrethrum were used in China as insecticides in ancient times and later in Middle Ages Persia. In Europe, an American merchant sold Persian dust as insect powder more than 200 years ago, which contained pyrethrum and showed excellent results against mosquitoes, cockroaches, bedbugs, and flies [22]. Many other plants used in the past contained insecticidal properties; for example, against cockroaches, elderberry flower had sufficient results [23], against weevils, extract of wormwood was used [24], and against aphids, the aqueous solution of tobacco was used [25].

In early 1000 BC, a natural chemical used by people to mitigate the problem of insect pests was inorganic sulfur, which was used for fumigation. Homer wrote in his book **The Iliad and the Odyssey** [26] about ritual sulfur used against lice and to purify the divine. Then, in 900 AD, arsenic was used, and later cryolite (Na_3AlF_6) and lead arsenate (PbHAsO_4) were used as cellular poisons in insect bait [27].

In the middle of the nineteenth century, the broad use of chemicals started to protect crops. For the control of the Colorado potato beetle, mixed copper acetoarsenite (Paris green) was successfully used in 1871 [28]. Paris green was successfully used around the globe until the middle of the twentieth century against the mosquito, a malaria vector belonging to the genus *Anopheles* [29, 30].

The most well-known chemical, DDT, was synthesized by chemist Othmar Zeidler, an Austrian student, in 1874 [31]. Paul Müller, a Swiss chemist, discovered its insecticidal properties while working at J. R. Geigy Ltd [22]. For this great contribution, Paul Müller was awarded the Nobel Prize in Medicine in 1948. After some time, it was observed that DDT not only kills insect pests but is also dangerous to humans, birds, mammals, and reptiles.

4. Types of pesticides

Each type of pesticide has its own characteristics and mode of action [Table 1]. The major types of pesticides used in agricultural practices are given below.

4.1 Carbamates

Carbamates are derivatives of carbamic acid ($\text{H}_2\text{N}-\text{COOH}$), an unstable compound where the hydrogen atom is replaced by an organic group (aryl or alkyl group). In modern agriculture, common examples used in fields nowadays are carbofuran, carbosulfan, and aldicarb [32]. The main function of carbamates is to inhibit the enzyme acetylcholinesterase. Acetylcholinesterase is an enzyme in insects that plays an important role in the transmission of nerve signals by breaking down the neurotransmitter acetylcholine at cholinergic synapses. By inhibiting this enzyme in pests, carbamates disturb nervous system signaling, which leads to paralysis and eventually causes the death of the insect. In non-target organisms, it also affects nerve signaling [33].

4.2 Organochlorines

OC is a group of insecticides that contain carbon and chlorine as essential elements [32]. They are the earliest synthetic pesticides but are now mostly banned, like DDT (dichlorodiphenyltrichloroethane), due to their impact on non-target organisms and persistence in the environment. Most OC pesticides, like endosulfan, are banned due to their bioaccumulation properties in living organisms [34].

4.3 Organophosphates

OPs are derivatives of phosphoric acid (H_3PO_4) or phosphonic acid (H_3PO_3). Both are inorganic acids. OPs are modified versions where organic molecules are

Pesticide type	Target organism	Mode of action	Human health risk	Environmental impact
Carbamates	Insects	Inhibit the acetylcholinesterase enzyme	Neurotoxicity	Harmful to non-target organisms
Organochlorines	Insects	Disrupt nerve transmission	Persistent in the body, causing cancer	Long-lasting in soil/ water, banned
Pyrethroid	Insects	Damage to sodium channels in nerve cells	Low to moderate neurotoxic risk	Toxic to aquatic life
Neonicotinoids	Insects	Bind to nicotinic acetylcholine receptors	Behavioral change in humans/Animals	Lethal to bees and pollinators
Organophosphate	Insects	Overstimulates the nervous system	Linked to Parkinson's and cancer	Highly toxic contaminants in water

Table 1.
Comparative toxicity of major pesticide types.

attached to the phosphorus atom [32]. OPs directly impact the nervous system of insects because they inhibit the synthesis of acetylcholinesterase, which leads to the accumulation of acetylcholine. This inhibition causes overstimulation, paralysis, and eventually the death of insects. Human health is also a major concern due to OPs because of their neurotoxic effects, which lead to neurodegenerative diseases such as Parkinson's disease [33].

4.4 Pyrethroids

Pyrethroids are a group of insecticides whose structure is similar to pyrethrins, which are naturally found in chrysanthemum flowers and possess insecticidal properties. These chemicals are used to control a wide range of pests, mostly in the agricultural sector, due to their potent activity. As a human health factor, OPs are more toxic than pyrethroids, but prolonged exposure to pyrethroids leads to serious health risks. In insects, they damage the nervous system by affecting sodium channels, which leads to repetitive nerve impulse transmission, paralysis, and ultimately death [35].

4.5 Neonicotinoids

Neonicotinoids are a new class of pesticides related to nicotine (a chemical found in tobacco plants with insecticidal properties) and are considered the most toxic category of pesticides. By binding to nicotinic acetylcholine receptors, they target the nervous system of insects and cause death. Neonicotinoids are generally considered target-specific pesticides with low risk to non-target organisms and the environment [36].

5. Classification of insecticides on the of target

Furthermore, the classification of insecticides on the basis of target is as follows:

5.1 Fungicides

As the name indicates, fungicides are types of pesticides used to inhibit the growth and reproduction of fungi and prevent further spreading and damage to plants. This enzyme damages the cell membrane, interferes with energy production, and stops respiration in fungi, ultimately causing death [37]. Some common examples of fungicides are difenoconazole, mancozeb, and pyraclostrobin. Mycotoxins (secondary toxins) produced by some fungi in grain cause serious illness and even death in humans and animals. Trichothecenes, fumonisins, aflatoxins, and ergot alkaloids are common examples of mycotoxins prevalent in crops [38].

Fungicides are classified on the basis of mode of action as single-site and multi-site fungicides. Single-site fungicides target a single site in fungi, while multi-site fungicides can target more than one site in fungal metabolic processes [34]. Fungicides can also be classified on the basis of chemical composition. Organic fungicides contain carbon atoms as essential components in their structure, but many early compounds were inorganic, containing metal ions toxic to fungi, such as tin, copper, and mercury, associated with sulfur [39].

5.2 Herbicides

Weeds are undesirable plants that compete with main crops for light, space, moisture, and nutrients, reducing yield quality and quantity. They can also interfere with harvesting tools and decrease the main yield. The toxic properties of weeds reveal negative impacts on animal and human health as well as ecosystems. In India, weeds cause almost 37.02% losses in crops, while insect pests cause 27.9% [40].

Herbicides, also called weedicides, are used to kill weeds that compete with the main crop. Herbicides are categorized into selective and non-selective types. Non-selective weedicides kill every plant or green part, and their toxic residues remain in the soil for extended periods. This led to the concept of selective herbicides, which target only specific weeds and leave the main crops unharmed. Some recent examples include atrazine, metolachlor, and glyphosate. Herbicides disturb the metabolic processes of unwanted plants, such as stopping photosynthesis, causing hormonal imbalance, and halting cell division. They can also be characterized as systemic and non-systemic based on translocation within plants and divided by the time of application as pre-emergence and post-emergence [34].

5.3 Nematicides

These are used against microscopic, segmented, worm-like invertebrates belonging to the phylum Nematoda, called nematodes. They cause major phytosanitary problems around the world. These parasitic nematodes typically range from 35 μm in width and 300–1000 μm in length. Nematodes mostly attack the root systems of plants, leading to decreased water and nutrient absorption capacity and ultimately reduced yield [41, 42]. Nematicides contain chemicals that prevent nematodes from feeding on plant roots, causing stunted growth. Commonly used nematicides include fumigants, carbofuran, and OPs. These are applied directly to the soil and divided into fumigants and non-fumigants based on chemical movement in the soil. Fumigants are biocidal and act on soil microorganisms, bacteria, and fungi, with high vapor pressure to diffuse through soil pores. The first fumigant nematicide was methyl bromide, used to control nematodes in tobacco crops, but its use disturbs environmental ecology [41, 43].

6. Advantages of synthetic pesticides

Pesticides are beneficial for farmers as they provide additional revenue by killing pests, rodents, and weeds [44]. This additional revenue may help increase living standards, especially in the education and health sectors [45]. Pesticides help produce quality food, high yields, and affordable prices, providing economic benefits to both producers and consumers [46]. By utilizing pesticides, almost 7 million people are prevented from dying from diseases like typhoid, fever, bubonic plague, and encephalitis [47]. In old times, pesticides were the only preventive or life-saving solution due to the lack of modern technology [48]. Even now, pesticides are used in public health by controlling mosquitoes [49].

Pesticides and fertilizers are important factors for increasing crop yield, while losses are caused by insect pest attacks, weeds, and diseases [50]. During the twentieth century, considerable production increases were observed in the USA [51],

China [52], Japan [53], and the United Kingdom [54], and significant economic losses were noted in the absence of pesticide use [50]. Annually, the USA saved almost 60 billion USD from crop protection by spending 9.2 billion USD on pesticides, achieving a net profit of 6.5 USD for every dollar spent [55]. Almost 40% of agricultural output was lost due to insect pests, weeds, and diseases [56].

7. Hazards of pesticides

According to a WHO report, almost 300,000 people die annually due to the overuse of pesticides [13]. The death rate is especially high in developing countries due to poor safety measures, lack of knowledge, and inefficient health safety protocols [57]. Problems associated with pesticides arise due to inhalation or direct contact with chemicals [58]. Literature indicates that women during gestation exposed to pesticides (DDT) have traces of DDT in breast milk and the umbilical cord [59]. It was noted that a relation exists between changes in birth weight and pesticide exposure [60]. Pesticides can penetrate in three ways: inhalation, ingestion, and skin contact [61, 62]. A major drawback is that the majority of suicide attempts involve the use of pesticides [63]. When non-judicious use of pesticides is applied on farms, it causes leaching or runoff into water bodies such as lakes, rivers, and dams [64]. These poisonous chemicals harm aquatic species like fish [65]. Acute toxicity causes unexpected, huge mortality among fish [66]. Several symptoms like suffocation, respiratory disorders, and neurological problems are associated with pesticides and become major reasons for fish deaths [67].

Among all pesticides, insecticides are considered the most toxic and harmful, whereas fungicides and herbicides rank second and third, respectively, in terms of toxicity. In natural ecosystems, pesticides enter in two ways depending on their chemical solubility. Water-soluble pesticides dissolve and leach into water bodies, infecting non-target organisms, while fat-soluble pesticides enter animal bodies through bioamplification and persist for extended periods, thereby entering the food chain [68].

8. Non-chemical management methods

Non-chemical control tools play a critical role in a sustainable pest management system, especially in grass and garden ecosystems where the overuse of pesticides is hazardous to human health, non-target organisms, and BC agents. These methods are intended to control the population of pests through ecological control, manipulation of habitats, and physical action instead of chemical elimination. The use of non-chemical practices helps decrease reliance on pesticides, conserve useful arthropods, and maintain the permanence of agroecosystems.

8.1 Introducing beneficial insects and wild, native plants

Introduction and preservation of advantageous insects is one of the important non-chemical approaches toward pest containment in lawns and gardens. Ladybird beetles (Coccinellidae), lacewings (Chrysopidae), hoverflies (Syrphidae), predatory mites, and parasitoid wasps are beneficial insects that actively feed on or parasitize common

garden pests like aphids, whiteflies, thrips, caterpillars, and scale insects. These are the natural predators of pests, which means that the population of the pests is controlled in a natural way, and the ecological balance is supported without the adverse effects of synthetic pesticides. BC agents are especially effective where the effects of chemical disturbance are kept to a minimum because exposure to insecticides tends to reduce their survival, fecundity, and foraging ability. Insect predators are often more sensitive to pesticides than target pests, which leads to a pest resurgence when the natural populations of enemies have been disrupted [69]. Preservation of useful insects thus lies in reducing chemical contributions and promoting alternative pest management plans.

Wild and native plants are important in maintaining the population of useful insects by supplying them with nectar, pollen, shelter, and alternative prey. The presence of flowering native vegetation increases the life span and reproductive success of predators and parasitoids, especially when pests are scarce. The introduction of native plants has been found to enhance the abundance of natural enemies and the effectiveness of BC in managed landscapes through habitat diversification [70]. Native plants are more suited to the local environment and need fewer inputs compared to exotic ornamental plants. They are added to the structure of lawn margins, garden borders, and non-cropped areas to enhance functional biodiversity. It has been established that diversified habitats minimize pest pressure through the intensification of predator-prey interactions and the stabilization of ecosystem dynamics [71]. BC agents like *Chrysoperla carnea* have been associated with the effectiveness of the floral resources available for adult insects to feed on. Research has shown that adult lacewings depend on sources of nectar and pollen to sustain reproduction and population maintenance in agroecosystems, and native flowering plants are important to non-chemical pest management systems [72].

8.2 Use of physical methods

Physical techniques include the embodiment of direct mechanical activities to control the population of pests without the use of chemical compounds in the environment. These methods are ecologically friendly, specific to the target, and do not conflict with BC measures. Physical control practices are best applied in lawn and garden systems where pest populations are localized and can be controlled by human or machine intervention.

8.2.1 Hand weeding

One of the most common physical pest control methods carried out in gardens and small-scale agricultural systems is hand weeding. The removal of weeds by hand eradicates the habitats of pests and alternative host plants, which lowers their establishment and population. Weeds are used by many insect pests as hiding places or alternative food sources before attacking cultivated plants. Crop hygiene and competition for nutrients, water, and light are all enhanced by manual weed removal. Hand weeding is not associated with the disruption of soil microbial communities or negative effects on beneficial arthropods, as opposed to chemical herbicides. This approach works especially well in organic farming systems and residential gardens where the use of chemicals is discouraged. Indirectly, hand weeding helps maintain predator and parasitoid populations, which are usually

negatively impacted by herbicides. The lower level of chemical interference enables natural enemies to operate well and increases pest control through ecological processes instead of the use of chemicals [73].

8.2.2 *Mulching*

Mulching involves a significant non-chemical method of suppressing weeds, regulating soil temperature, conserving moisture, and disrupting the life cycle of pests. Compost, wood chips, crop residues, and straw are organic mulches that prevent the emergence of weeds and reduce oviposition areas for insects. Another benefit of mulches is their ability to improve the structure of the soil, as well as the proliferation of beneficial microorganisms in the soil, which indirectly leads to the health of plants and their resistance to pest attacks. Plants that are healthier are not vulnerable to insects and diseases, and thus fewer chemical interventions are required. Moreover, mulched habitats also provide good environments for ground predators like beetles and spiders, who help in the suppression of pests. Some studies have indicated that mulching lowers the population of soil-dwelling pests and reduces the transmission of plant pathogens by altering the microclimate at the soil surface [74]. Integrated pest management concepts also advocate the use of organic mulches, as they improve BC with reduced environmental disturbance. The long-term success of BC agents (e.g., by maintaining predator-friendly habitats via mulching) and the minimization of the risks of pest resurgence, especially when the use of selective chemicals cannot be avoided, are supported by the principles of integrated pest management [69].

8.2.3 *Setting traps*

Trapping is a good physical method of managing pests, which is applied to monitor and control their populations. The most common traps are pheromone traps, sticky traps, light traps, and baited traps. These tools are useful for the early detection of pest infestations and decision-making based on the population threshold of the pests, rather than routine pesticide application. Pheromone traps are species-specific and affect mating behavior by attracting male insects and, as a result, reduce reproductive success as well as slow population growth. Lawn and garden systems are well-known for using sticky traps to monitor flying pests, including whiteflies, leaf miners, and thrips. These traps also provide useful data on the dynamics and infestation levels of pests. Traps are especially effective when combined with the use of BC measures because they minimize pest pressure without negatively affecting other insects that are beneficial to humans. Traps do not leave toxic residues or alter predator-prey interactions as chemical sprays do. Their application leads to reduced chemical use and the provision of sustainable pest management outcomes [75]. Trap placement, density, and frequent monitoring are factors that determine trap effectiveness. Trapping is an important part of non-chemical pest control in lawn and garden ecosystems, in combination with habitat control management and physical control [76].

9. Effect on BC agents

Natural enemies are organisms that naturally kill insects and pests [77]. BC agents are also reared in labs and released artificially to control insect pests [78].

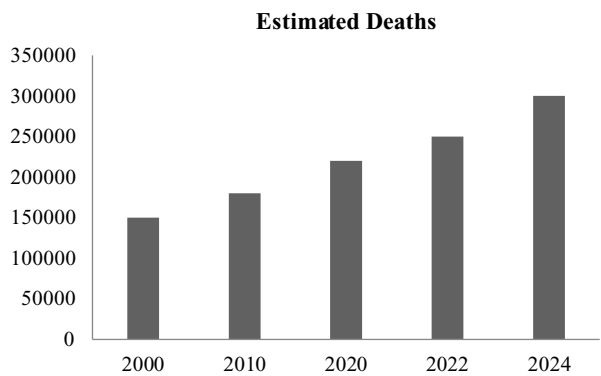


Figure 1.
The death rate due to the hazards of pesticides is continuously increasing and reaches up to 220,000 deaths in 2024.

Pesticides reveal harmful effects on BC agents or natural enemies [Figure 1]. Using broad-spectrum pesticides like carbamates, pyrethroids, and OPs significantly decreases populations of beneficial insects such as beetles and bees. Synergistic effects of triazole or imidazole and pyrethroids are very harmful to honey bee populations [79]. Even low doses of imidacloprid cause negative impacts on the foraging behavior [80] and learning capacity of bees [81]. At the start of the twentieth century, honey bee populations suddenly decreased, which became a major concern for the food industry as one-third of total food production depends on bee pollination. It was reported that honey and wax from hives contained mixtures of different pesticides, with a significant share of neonicotinoids [82] [Table 2]. Pesticides have a more toxic impact on natural enemies than on pests [83]. Pests develop resistance more quickly than natural enemies, so after pesticide application, natural enemies die more quickly than pests [84]. Killing natural enemies during chemical applications promotes resurgence (secondary outbreak) of pests [84]. Resurgence is a major problem because it is the reappearance of secondary outbreaks; to decrease its chance, we must ensure the minimum use of selective chemicals that reveal minimal negative impact on BC agents.

Ecosystems component	Observed effect	Pesticide class
Soil Microbes	Reduced nitrogen fixation, microbial death	Herbicides, fungicides
Birds	Mortality, neurological disruption, and reduced reproduction	Organochlorine, granular insecticides
Fish	Protein degeneration, immune suppression, and behavioral changes	Organophosphates, carbamates
Bees	Memory loss, decreased foraging, colony collapse	Neonicotinoids, triazoles
Biocontrol Agents	Reduced population, ineffective pest control	Pyrethroids, organophosphates

Table 2.
Effect of pesticides on different ecosystems.

10. Objective

Many countries are agricultural, and their main income source is exporting agricultural products. For example, the USA earns \$1.3 trillion by exporting agricultural commodities worldwide [85], and China earns USD 51.03 billion [68]. Revenue from exports is used for the betterment of society and for increasing living standards. However, the major reason for this production is the use of synthetic fertilizers and chemicals for pest control. Therefore, the main objective of this manuscript is to provide a clear picture of the hazards posed by harmful chemicals on humans, fishes, and BC agents, and to help take judicious action against the sensitivity of the problem.

11. Methodology

The data and information for this chapter were collected from various primary sources, such as research articles, and secondary sources, including books, reports, magazines, news, and online platforms like Google, Google Scholar, ResearchGate, etc., and were reviewed extensively for the preparation of this manuscript.

12. Conclusion and future directions

The majority of farmers are not aware of the potential risks associated with pesticide usage. They do not have enough information regarding the types of pesticides, levels of poison, and safety measures. Pesticide contamination causes significant loss to humans, the environment, and BC populations. To minimize its impact, we must decrease chemical contamination.

We must adopt new techniques and tools to reduce overall pesticide usage without decreasing crop quality and quantity. We must develop systems of pesticide-resistant BC agents to ensure their survival and control secondary pest outbreaks. This pest management technique will lead toward sustainable pest management in agroecosystems. The development of resistance in BC agents has been reported [86]. Along with this, we need to check the pesticide impact on BC agents regarding blood biochemical parameters, growth disorders, chromosomes, behavioral variations, genotoxicity, immune system, and enzyme functioning. It is the demand of the time to integrate different discipline studies like environmental chemistry, ecology, population biology, conservation biology, and toxicology to estimate the pesticide impact on the environment [87].

Funding

The authors have received no funding for this project.

Credit authorship contribution statement

Arbaz Khan: Writing – Original Draft, Visualization, Software, Methodology, Investigation

Muhammad Yaseen: Writing, Editing, and Proof Reading

Sehrish Zafar: Formal analysis, administration, and conceptualization.

Sarfraz Ali Shad: Supervision Project

Declaration of competing interest

The authors declare no relevant financial or nonfinancial interests.

Acknowledgments

I am expressing my sincere gratitude to the Insecticide Resistance (Lab IR) at the Department of Entomology, Faculty of Agriculture, BZU, as well as to Sehrish Zafar and Mesam Abbas for their help in the completion of the manuscript.

Author details

Arbaz Khan^{1*}, Muhammad Yaseen², Sehrish Zafar³ and Sarfraz Ali Shad⁴

1 Department of Ecology and Nature Management, Institute of Environmental Engineering, Peoples' Friendship University of Russia (RUDN), Moscow, Russia

2 Department of Horticulture, Bahauddin Zakariya University, Multan, Pakistan

3 Department of Food Science and Technology, Bahauddin Zakariya University, Multan, Pakistan

4 Department of Entomology, Bahauddin Zakariya University, Multan, Pakistan

*Address all correspondence to: kipsian1314@gmail.com

IntechOpen

© 2026 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Government of Pakistan (GOP). Pakistan Economic Survey 2021–22. Ministry of Finance. 2022. Available from: https://www.finance.gov.pk/survey_2022.html
- [2] United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects 2022: Summary of Results. United Nations. 2023. Available from: <https://population.un.org/wpp/>
- [3] Wilson C. Environmental and human costs of commercial agricultural production in South Asia. *International Journal of Social Economics*. 2000;27(7-8):816–846
- [4] Abubakar Y, et al. Pesticides, history, and classification. In: Egbuna C, Sawicka B, editors. *Natural remedies for pest, disease and weed control*. London: Elsevier; 2020. p. 29–42
- [5] van den Berg H, et al. Management of insecticides for use in disease vector control: a global survey. *BMC Infectious Diseases*. 2021;21:468
- [6] Ntow WJ, et al. Farmer perceptions and pesticide use practices in vegetable production in Ghana. *Pest Management Science*. 2006;62:356–365
- [7] Theenoor R, et al. Harmonizing Control: Understanding the Complex Impact of Pesticides on Parasitoid Wasps for Enhanced Pest Management. *Current Opinion in Insect Science*. 2024;65:101236
- [8] AbuQamar SF, et al. Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Marine Pollution Bulletin*. 2024;206:116613
- [9] Tison L, et al. Transfer and bioaccumulation of pesticides in terrestrial arthropods and food webs: state of knowledge and perspectives for future research. *Chemosphere*. 2024;357:142036
- [10] Talebi K, et al. Impacts of pesticides on arthropod biological control agents. *Pest Technology*. 2008;2:87–97
- [11] Lisi F, et al. Non-target effects of neurotoxic insecticides on *Ganaspis cf. brasiliensis*, a classical biological control agent of the spotted wing *Drosophila*. *CABI Agriculture and Bioscience*. 2024;5:48
- [12] Carson R. *Silent Spring*. Boston: Houghton Mifflin; 1962
- [13] Gulzar M, et al. Use of Insecticides and their impact on viral diseases in Humans, Animals and Environment. *Hosts and Viruses*. 2024;11:64–77
- [14] Kamalesh R, et al. Progress in environmental monitoring and mitigation strategies for herbicides and insecticides: A comprehensive review. *Chemosphere*. 2024;352:141421
- [15] Mengistu DA, et al. Pesticide safety practice and its public health risk in African regions: systematic review and meta-analysis. *BMC Public Health*. 2024;24:2295
- [16] Kaur R, et al. Pesticides: An alarming detrimental to health and

environment. *Science of The Total Environment*. 2024;**915**:170113

[17] Al-Mamun A. Pesticide degradations, residues and environmental concerns. In: Mohidus K, Mohammad SR, editors. *Pesticide Residue in Foods: Sources, Management, and Control*. Switzerland: Springer; 2017. p. 87–102

[18] Smith T, Taylor MS. Some morphological and biological characters of the spirilla (*Vibrio fetus*, n. sp.) associated with disease of the fetal membranes in cattle. *The Journal of Experimental Medicine*. 1919;**30** (4):299–311

[19] Douth RL. Vice, virtue, and the vedalia. *Bulletin of the Entomological Society of America*. 1958;**4**(4):119–123

[20] Lounsbury C. The pioneer period of economic entomology in South Africa. *Journal of the Entomological Society of Southern Africa*. 1940;**3** (1):09–29

[21] Lindquist EE. *Digamasellus Berlese*, 1905, and *Dendrolaelaps Halbert*, 1915, with descriptions of new taxa of Digamasellidae (Acarina: Mesostigmata). *The Canadian Entomologist*. 1975;**107**(1):1–43

[22] Davies TG, Field LM, Usherwood PN, Williamson MS. DDT, pyrethrins, pyrethroids and insect sodium channels. *IUBMB Life*. 2007;**59**(3):151–162. DOI: 10.1080/15216540701352042

[23] Dagaev M (1997). *Baleen aggressors or everything about the war on cockroaches*. Iayza, Lan', Moskva. 112. St. Petersburg: Lan. 5-86617-024-8. Available from: <https://www.libex.ru/detail/book950400.html>

[24] Ignatowicz S, Wesołowska B. Insecticidal and deterrent properties of extracts from herbaceous plants. *Ochrona Roślin*. 1994;**38**(9):14–15. DOI: 10.5555/19961101822

[25] Nisar MS, Ahmed S, Ashfaq M, Sahi ST. Effect of leaf and seed extracts of *Jatropha curcas* linn. on mortality and tunneling of subterranean termites, *Odontotermes obesus* (Ramb.) (Termitidae: Isoptera). *Pakistan Journal of Life and Social Sciences*. 2012;**10** (1):33–38. http://www.pjlss.edu.pk/pdf_files/2012_1/33-38.pdf

[26] Rutherford RB. From the Iliad to the Odyssey. *Bulletin of the Institute of Classical Studies*. 1993;**38**(1):37–54

[27] Isman MB. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*. 2006;**51**(1): 45–66

[28] Alyokhin A, Guillemette R, Choban R. Stimulatory and Suppressive Effects of Novaluron on the Colorado Potato Beetle Reproduction. *Journal of Economic Entomology*. 2009;**102** (6):2078–2083. DOI: 10.1603/029.102.0609

[29] Symes CB. Some Recent Progress in the Study of Insecticides and Their Application for the Control of Vectors of Disease. *Journal of the Royal Sanitary Institute*. 1952;**72**(5):498–514. DOI: 10.1177/146642405207200505

[30] Majori G. Short history of malaria and its eradication in Italy with short note on the fight against the infection in the Mediterranean Basin. *Mediterranean Journal of Hematology and Infectious Diseases*. 2012;**4**(1):

e2012016. DOI: 10.4084/
 MJHID.2012.016

[31] Bate P, Robert G. Toward more user-centric OD: Lessons from the field of experience-based design and a case study. *The Journal of Applied Behavioral Science*. 2007;**43**(1):41–66. DOI: 10.1177/0021886306297014

[32] Insecticide Resistance Action Committee (IRAC). IRAC mode of action classification scheme. 2025. Available from: <https://irac-online.org/>

[33] Colovic MB, et al. Acetylcholinesterase inhibitors: pharmacology and toxicology. *Current Neuropharmacology*. 2013;**11**:315–335

[34] Garud A, et al. A scientific review of pesticides: Classification, toxicity, health effects, sustainability, and environmental impact. *Cureus*. 2024;**16**:e67945

[35] Katsuda Y. Progress and future of pyrethroids. In: Matsuo N, Mori T, editors. *Pyrethroids: From Chrysanthemum to Modern Industrial Insecticide*. Berlin: Springer; 2012. p. 1–30

[36] Jeschke P, Nauen R. Neonicotinoids—from zero to hero in insecticide chemistry. *Pest Management Science*. 2008;**64**(11):1084–1098

[37] Sharma I. Phytopathogenic fungi and their biocontrol applications. In: Vijay KS, Maulin PS, Shobhika P, Ajay K, editors. *Fungi bio-prospects in sustainable agriculture, environment and nano-technology*. London: Elsevier; 2021. p. 155–188

[38] Zain ME. Impact of mycotoxins on humans and animals. *Journal of Saudi Chemical Society*. 2011;**15**(2):129–144

[39] McGrath MT. What are fungicides. *The Plant Health Instructor*. 2004;**4**: 109–115. DOI: 10.1094/PHI-I-2004-0825-01

[40] Mondal D, et al. Yield loss assessment of rice (*Oryza sativa* L.) due to different biotic stresses under system of rice intensification (SRI). *Journal of Entomology and Zoology Studies*. 2017;**5**:1974–1980

[41] Ebone LA, et al. Nematicides: history, mode, and mechanism action. *Plant Science Today*. 2019;**6**: 91–97

[42] Makhubu F, et al. South African plants with nematocidal activity against root-knot nematodes: A review. *South African Journal of Botany*. 2021;**139**:183–191

[43] Cabrera Motta JA. Isolation, characterization and interactions of soil microorganisms involved in the enhanced biodegradation of non-fumigant organophosphate nematicides [thesis]. Universitäts-und Landesbibliothek Bonn; 2009

[44] Cooper J, Dobson H. The benefits of pesticides to mankind and the environment. *Crop Protection*. 2007;**26** (9):1337–1348

[45] Rosegrant MW, Ringler C, Benson T, Diao X, Resnick D, Thurlow J, Torero M, Orden D. Agriculture and achieving the Millennium Development Goals. World Bank. 2005. Available from: <http://documents.worldbank.org/curated/en/656581468339659645>

[46] Popp J, Petč, et al. Pesticide productivity and food security. A review. *Agronomy for Sustainable Development*. 2013;**33**:243–255

- [47] Poudel S, et al. Pesticide use and its impacts on human health and environment. *Environmental Ecosystem Science*. 2020;**4**:47–51
- [48] Egler FE. Pesticides—in our ecosystem. *American Scientist*. 1964;**52** (1):110–136. <http://www.jstor.org/stable/27838919>
- [49] Cuervo-Parra JA, et al. Mosquito-borne diseases, pesticides used for mosquito control, and development of resistance to insecticides. In: Stanislav T, editor. *Insecticides resistance*. Rijeka: InTechOpen; 2016. p. 111–134
- [50] Aktar MW, et al. Impact of pesticides use in agriculture: their benefits and hazards. *Interdisciplinary Toxicology*. 2009;**2**:1
- [51] Warren G. Spectacular increases in crop yields in the United States in the twentieth century. *Weed Technology*. 1998;**12**(4):752–760
- [52] Huang J, Rozelle S, Rosegrant M. China's food economy to the 21st century: Supply, demand, and trade. *Economic Development and Cultural Change*. 1999;**47**(4):737–766. DOI: 10.1086/452435
- [53] Waswo A, Yoshiaki N. *Farmers and village life in twentieth-century Japan*. London: Routledge Curzon London; 2003
- [54] Brassley P. Output and technical change in twentieth-century British agriculture. *The Agricultural History Review*. 2000;**48**:60–84
- [55] Gianessi LP. The value of insecticides in U.S. crop production. CropLife Foundation, Crop Protection Research Institute; 2009. Available from: <https://croplifefoundation.org/press.com/resources/benefits-studies/insecticides/>
- [56] Mahmood I, et al. Effects of pesticides on environment. In: Hakeem K, Akhtar M, Abdullah S, editors. *Plant, soil and microbes: volume 1: implications in crop science*. Cham: Springer; 2016. p. 253–269
- [57] Mustafa BM, Hassan NE. Water Contamination and Its Effects on Human Health: A Review. *Journal of Geography, Environment and Earth Science International*. 2024;**28** (1):38–49
- [58] Gajalakshmi G, Meenakshi S. Human Causes and Consequences: An Analysis on Environmental Pollutants and Their Effects on Human Health. *African Journal of Biomedical Research*. 2024;**27**(3S):3003–3016
- [59] Sharma M. Presence of organochlorine pesticides in breast milk, maternal blood and cord blood: An alarming situation. *Journal/Publisher details needed*. n.d. Available from: <https://pubmed.ncbi.nlm.nih.gov>
- [60] De Joode BVW, et al. Pesticide exposure, birth size, and gestational age in the ISA birth cohort, Costa Rica. *Environmental Epidemiology*. 2024;**8**:e290
- [61] Baig A, et al. Harmful Health Impacts of Heavy Metals and Behavioral Changes in Humans. *Indonesian Journal of Agriculture and Environmental Analytics*. 2024;**3**:77–90
- [62] Yadav CS, et al. *Bioremediation of Environmental Toxicants: Toxicants, Sources, Mechanism, Impact on Human Health, and Bioremediation Approaches*. Boca Raton (FL): CRC Press; 2024

- [63] Frengidou E, et al. Pesticide exposure or pesticide poisoning and the risk of depression in agricultural populations: a systematic review and meta-analysis. *Journal of Agromedicine*. 2024;**29**:91–105
- [64] Singh M. Pesticide predicament: Exploring environmental and health impacts, and possible eco-friendly solutions. *International Journal of Environmental Health Science*. 2024;**6**:38–47
- [65] Hasan AM, et al. A review of the neurobehavioural, physiological, and reproductive toxicity of microplastics in fishes. *Ecotoxicology and Environmental Safety*. 2024;**282**:116712
- [66] Ullah A, et al. Induced-Toxicity of Pesticides on Edible Freshwater Fishes in Pakistan: A Review. *Sarhad Journal of Agriculture*. 2024;**40**(1):195–212
- [67] EL-Bouhy ZM, et al. Acute Toxicity of an Emerging Insecticide, Pymetrozine, to the Nile tilapia. *Egyptian Journal of Aquatic Biology & Fisheries*. 2024;**28**(5):265–279
- [68] Zhang D, Sun Z. Comparative advantage of agricultural trade in countries along the belt and road and China and its dynamic evolution characteristics. *Foods*. 2022;**11**(21):3401
- [69] Khan A, Shad SA. Inheritance Pattern and Cross Resistance Assessment of Flonicamid Resistance in the Biological Control Agent *Chrysoperla carnea* (Neuroptera: Chrysopidae). *Jurnal Riset Perkebunan*. 2025;**6**(2):92–103
- [70] Landis DA, Wratten SD, Gurr GM. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology*. 2000;**45**. DOI: 10.1146/annurev.ento.45.1.175
- [71] Symondson W, Gurr G, Wratten S, Snyder W, Read D, Editors. *Biodiversity and insect pests: Key issues for sustainable management*. John Wiley & Sons; 2012. DOI: 10.1002/9781118231838
- [72] Desneux N, Decourtye A, Delpuech J-M. The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*. 2007;**52**. DOI: 10.1146/annurev.ento.52.110405.091440
- [73] Altieri MA, Nicholls CI, Ponti L. Crop diversification strategies for pest regulation in IPM systems. In: Radcliffe EB, Hutchinson WD, Cancelado RE, editors. *Integrated Pest Management*. Cambridge: Cambridge University Press; 2009. p. 116–130
- [74] Hooks CR, Johnson MW. Impact of agricultural diversification on the insect community of cruciferous crops. *Crop Protection*. 2003;**22**(2):223–238
- [75] Kogan M. Integrated pest management: Historical perspectives and contemporary developments. *Annual Review of Entomology*. 1998;**43**. DOI: 10.1146/annurev.ento.43.1.243
- [76] Miller JR, Cowles RS. Stimulodeterrent diversion: A concept and its possible application to onion maggot control. *Journal of Chemical Ecology*. 1990;**16**(11):3197–3212. DOI: 10.1007/BF00979619
- [77] Flint ML, Dreistadt SH. *Natural enemies handbook: The illustrated guide to biological pest control*. University of California Press; 1998. <https://archive.org/details/naturalenemiesha0000flin>

- [78] Parra JRP, Coelho A. Insect rearing techniques for biological control programs, a component of sustainable agriculture in Brazil. *Insects*. 2022;**13** (1):105
- [79] Schuhmann A, et al. Interaction of insecticides and fungicides in bees. *Frontiers in Insect Science*. 2022;**1**:808335
- [80] Tan K, et al. Imidacloprid alters foraging and decreases bee avoidance of predators. *Public Library of Science One*. 2014;**9**:e102725
- [81] Decourtye A, et al. Learning performances of honeybees (*Apis mellifera* L) are differentially affected by imidacloprid according to the season. *Pest Management Science*. 2003;**59**: 269–278
- [82] Buckley R. Environmental impacts. In: David B. Weaver, editor. *The encyclopedia of ecotourism*. Wallingford UK: Cabi Publishing; 2001. p. 379–394
- [83] Schmidt-Jeffris RA. Nontarget pesticide impacts on pest natural enemies: Progress and gaps in current knowledge. *Current Opinion in Insect Science*. 2023;**58**:101056
- [84] Keasar T, et al. Dynamic economic thresholds for insecticide applications against agricultural pests: Importance of pest and natural enemy migration. *Journal of Economic Entomology*. 2023;**116**:321–330
- [85] Westcott P. USDA agricultural projections to 2019 (OCE-2010-1). U.S. Department of Agriculture, Economic Research Service; 2010. <https://www.ers.usda.gov/publications/pub-details/?pubid=37808>
- [86] Khan A, Shad SA. Inheritance Pattern and Cross-Resistance Assessment of Flonicamid Resistance in the Biological Control Agent *Chrysoperla carnea* (Neuroptera: Chrysopidae). *Jurnal Riset Perkebunan*. 2025;**6**(2):92–103
- [87] Macneale KH, et al. Pesticides, aquatic food webs, and the conservation of Pacific salmon. *Frontiers in Ecology and the Environment*. 2010;**8**:475–482

Chapter 5

Environmental Effects and Risk Control of Neonicotinoid Insecticides

Xiaoning Wang, Chuanxi Yang, Yongkun Wu, Mingfang Zhang, Kaipeng Sun, Yiyong Xu and Ziheng Wan

Abstract

Neonicotinoid insecticides (NEOs) have become the most widely used class of insecticides globally since the 1990s, owing to their high insecticidal efficacy, broad spectrum, and low acute toxicity to mammals. However, their widespread application, high water solubility, environmental persistence, and systemic properties have led to ubiquitous contamination in various environmental media, biota, and food products. This chapter systematically reviews the emission pathways, environmental distribution, and ecological and human health risks of NEOs and summarizes the latest advances in risk control technologies. NEOs are primarily emitted through industrial wastewater discharge, agricultural runoff, and sewage treatment plant effluents, and are frequently detected in water, soil, air, and biological matrices (human urine, tea, milk, and wildlife). Human exposure occurs mainly *via* dietary intake, with children and neonates showing higher vulnerability due to maternal–fetal transfer and immature metabolic systems. Ecologically, NEOs pose significant risks to non-target organisms, including birds, bees, and aquatic invertebrates, affecting their health, behavior, reproduction, and survival. Risk control strategies for NEOs include physicochemical technologies (adsorption, photocatalysis, Fenton-like processes) and biotechnologies (microbial degradation, phytoremediation), each with unique advantages and limitations. Key challenges remain the low detectability of transformation products, their potential toxicity, and the need for synergistic control strategies. This chapter provides a comprehensive overview of the environmental effects and environmental risk prevention and control for emerging contaminants, NEOs.

Keywords: neonicotinoid insecticides, environmental effects, risk control, environmental exposure, health effects

1. Introduction

Since their commercialization in the early 1990s, neonicotinoid insecticides (NEOs) have transformed agricultural pest management, replacing older classes

such as organophosphates and carbamates [1]. Their unique mode of action, targeting insect nicotinic acetylcholine receptors (nAChRs), delivers high selectivity and efficacy against a broad range of sucking and chewing pests, while exhibiting low acute toxicity to mammals [2]. By 2014, NEOs accounted for over 25% of the global insecticide market, registered in 120 countries for use on more than 140 crops [3]. In China, one of the world's largest agricultural economies, NEOs are extensively employed in seed coating, foliar spraying, and soil application, supporting high crop yields but also raising concerns about environmental contamination [4].

Despite their agricultural benefits, NEOs' environmental behavior has sparked growing alarm. Unlike traditional insecticides, NEOs are systemic-absorbed by plant roots or leaves and translocated to all tissues, including nectar, pollen, and fruits [5]. Among these cases, 101 incidents – resulting in the death of at least 734 animals – were linked to the agricultural application of imidacloprid (IMI) as a seed treatment. The primary affected species included gray partridges (*Perdix perdix*) and three pigeon species (*Columba palumbus*, *Columba livia*, and *Columba oenas*). Notably, over 70% of these mortality incidents occurred during the autumn cereal sowing period [5]. NEOs residues have been detected in diverse environmental matrices, from urban streams to remote agricultural soils, and even in human biological samples such as urine, serum, and cerebrospinal fluid [6].

The ecological risks of NEOs are particularly well-documented for pollinators. Honeybees exposed to sublethal concentrations exhibit reduced foraging activity, impaired navigation, and colony collapse [7]. Beyond bees, NEOs affect birds, aquatic invertebrates, and soil microorganisms, disrupting food webs and ecosystem function [8, 9]. For humans, chronic exposure has been linked to neurodevelopmental disorders, insulin resistance, reduced semen motility, and increased risks of osteoporosis and cancer [10]. Vulnerable populations, such as children and neonates, face elevated risks due to maternal–fetal transfer of NEOs and their metabolites [11].

To address these challenges, extensive research has focused on developing efficient risk control technologies, including physicochemical methods (adsorption, advanced oxidation processes) and biotechnologies (microbial degradation, phytoremediation) [12]. Oxygen-doped graphitic carbon nitride (OCN) activated peroxymonosulfate (PMS) for IMI degradation, enhancing PMS adsorption, electron transfer, redox sites, light absorption, and charge separation. OCN-10/PMS removed 94.5% of IMI (3.0 mg/L) in 2 hours; its k (1.501 h^{-1}) was 30.3 times higher than $\text{g-C}_3\text{N}_4/\text{PMS}$ (0.048 h^{-1}) [13]. However, many of these technologies remain in the laboratory stage, with practical application limited by factors such as cost, efficiency, and environmental compatibility. Additionally, the complexity of NEOs' transformation products, some of which are more toxic than the parent compounds, poses new hurdles for risk assessment and control [14].

As shown in **Figure 1**, this chapter synthesizes the latest research on NEOs, covering their emission pathways, environmental distribution, ecological and human health risks, and risk control technologies. It also identifies key knowledge gaps and future research directions to inform policy-making and environmental management.

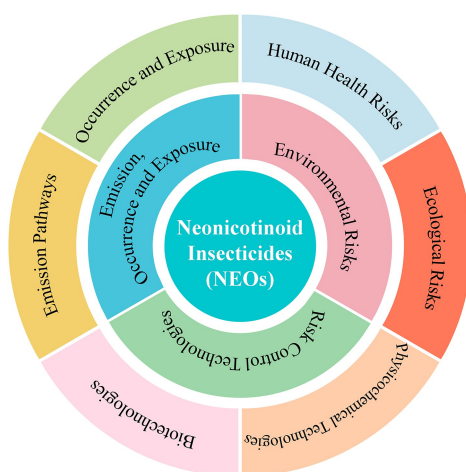


Figure 1.
 Overview of environmental effects and risk control of NEOs.

2. Emission, occurrence, and exposure of neonicotinoid insecticides

2.1 Emission pathways

NEOs enter the environment through multiple pathways, primarily driven by anthropogenic activities such as industrial production, agricultural application, and wastewater discharge [15].

Industrial emission: During NEOs manufacturing, untreated or partially treated wastewater containing high concentrations of parent compounds and by-products is discharged into water bodies, posing acute risks to aquatic organisms [15]. Health Canada's Pest Management Regulatory Agency (PMRA) has classified IMI as persistent and assigned it a high leaching potential. Globally, neonicotinoids have been detected in diverse water bodies, with concentrations typically falling in the low $\mu\text{g/L}$ range [16].

Agricultural non-point source pollution: Agricultural application is the largest source of NEOs in the environment. Applied as seed coatings, soil drenches, foliar sprays, or trunk injections, NEOs enter the environment through runoff, leaching, volatilization, or crop residue decomposition [17]. Seed coating, common for corn, soybeans, and wheat, releases NEOs into soil and water during planting or rainfall [18]. Studies in China's Yangtze River Delta found agricultural runoff contributed 60–80% of NEO loads in surface water, with thiamethoxam (TMX) and IMI as dominant compounds [19].

Sewage treatment plant (STP) discharge: Flow-weighted daily composite samples were analyzed *via* isotope dilution liquid chromatography-tandem mass spectrometry (ID–LC–MS/MS). Mass balance analysis indicated insignificant removal of IMI ($p = 0.09$, 95% CI) and limited removal of the sum of acetamiprid (ACE) and its degradate N-desmethyl-ACE (N-dm-ACE, $18 \pm 4\%$, $p = 0.01$, 95% CI). Clothianidin (CLO) was detected only intermittently, whereas TMX, thiacloprid (THD), and dinotefuran (DIN) were not detected at all [20]. Studies show STP effluents in China contain NEO concentrations ranging from 0.01 to 0.5 $\mu\text{g/L}$, which can accumulate in receiving water bodies over time [21].

2.2 Environmental occurrence

2.2.1 Water

NEOs are frequently detected in surface water, groundwater, and drinking water globally, with concentrations varying by region, land use, and hydrological conditions. In China, surface water samples from agricultural areas have NEO concentrations ranging from 0.001 to 4.68 µg/L, with TMX, IMI, and ACE as the most common compounds [22]. A nationwide survey of drinking water in China found 92–98% of samples contained detectable NEOs, with a median total concentration of 0.27 µg/L [22]. The maximum total neonicotinoid concentration in a single sample reached 400 ng/L, which provides critical baseline data for evaluating the potential ecological risks of neonicotinoid accumulation in the study area [23].

Groundwater contamination by NEOs is a growing concern, particularly in intensively agricultural areas. In China's Pearl River Delta, the Σ6NII concentrations (six neonicotinoids, i.e., IMI, CLO, ACE, imidaclothiz (IMZ), DIN, and flonicamid (FLO), range [median]) in soils were 0.26–390 (23) ng/g for vegetable farms, 0.26–280 (6.1) ng/g for rice paddies, and 0.26–120 (5.0) ng/g for fruit farms. NEOs are more frequently detected in vegetable soils (higher levels) than in rice/fruit soils due to frequent NEOs use [24]. NEOs can leach into groundwater through soil pores, especially in sandy soils with low organic matter content.

2.2.2 Soil

Soil serves as a major sink for NEOs, with concentrations strongly influenced by application rate, soil properties, and climate. The occurrence and ecological risks of 10 NEOs in Chinese field soils (rice, wheat, corn) were investigated using an optimized UPLC–MS/MS method (LOQ = 0.01–1.7 ng/g; RSD). <12.21%), 10 NEOs were quantified in 69 soil samples (23 rice, 18 corn, 28 wheat). NEOs detection frequency (DF) was 100% across all samples; individual DFs: IMI (100%) > TMX (88.4%) > CLO (87.0%) > ACE (46.4%) > DIN (7.2%) > nitenpyram (NTP, 1.4%). Mean total NEO concentrations showed crop specificity: wheat (1.77–214.55 ng/g) > corn (0.79–97.53 ng/g) > rice (0.75–72.97 ng/g) [4].

NEOs act as nicotinic acetylcholine receptor (nAChR) agonists, binding strongly to insect central nervous system nAChRs. This binding causes nervous overstimulation at low concentrations and receptor blockage, paralysis, and death at higher concentrations [17]. Owing to their greater affinity for insect versus vertebrate nAChRs, they exhibit selective toxicity to insects [25].

Chemically, they fall into three groups: N-nitroguanidines (IMI, TMX, CLO, DIN), nitromethylenes, and N-cyanoamidines (ACE, THD) [1]. Their high insect toxicity is exemplified by honeybee oral LD₅₀ values: 5 ng/insect (IMI) and 4 ng/insect (CLO) ~ 1/10,000th of DDT's LD₅₀ in honeybees [26]. Soil organic matter content, pH, and clay content affect NEOs' adsorption and degradation; higher organic matter increases adsorption, reducing leaching but prolonging persistence [27].

2.2.3 Air

NEOs enter the atmosphere through volatilization from soil or foliage, or *via* wind erosion of contaminated dust particles. Airborne NEO concentrations are

generally low (pg/m^3 to ng/m^3) but widespread. In urban areas of China, PM_{2.5} samples contained IMI and ACE concentrations ranging from 0.01 to 0.1 ng/m^3 , with higher levels near agricultural fields [28]. In agricultural areas, wind-driven dust from seed coating operations can lead to short-term high concentrations of NEOs in the air, posing inhalation risks to farmworkers [18].

2.3 Environmental exposure

2.3.1 Human

Human exposure to NEOs is widespread, as evidenced by their detection in urine, serum, cerebrospinal fluid, and breast milk. Urine is the most commonly used matrix for biomonitoring, as NEOs are rapidly metabolized and excreted within three days [29]. Six target NEOs – IMI, TMX, ACE, CLO, THD, and DIN – were detected in over 90% of urine samples from 305 children, indicating widespread exposure in this population. Their median urinary concentrations were 0.13, 0.21, 0.01, 0.19, 0.002, and 1.64 $\mu\text{g/L}$, respectively [30].

Neonates are exposed to NEOs *via* maternal-fetal transfer. Tang et al. determined concentrations of 13 NEOs and their metabolites in first-void urine from 92 preterm and full-term newborns in southern China (2020–2021) [11]. NEOs/metabolites were detected in 91 samples, with over 93% containing compound cocktails – confirming maternal-fetal transfer. *N*-dm-ACE, IMZ, CLO, and FLO were the most prevalent analytes, with detection frequencies of 59 – 87% and median concentrations of 0.024 – 0.291 ng/mL [11].

Serum samples also confirm human exposure. Following exposure, NEOs undergo Phase I/II metabolism *via* human cytochrome P450 enzymes. However, the toxicities of parent NEOs and their metabolites remain unclear, and human NEO biotransformation rates and pathways are poorly understood. Conjugated NEOs accounted for 53% of total NEOs. NEO Phase II metabolites are linked to oxidative DNA damage, and serum-conjugated IMI, DIN, and 5-OH-IMI correlated positively with oxidative stress [31].

2.3.2 Plants

NEOs are systemic in plants, meaning they are absorbed and translocated to all tissues, including leaves, fruits, and seeds. Tea is particularly vulnerable to NEO contamination due to intensive pesticide use in plantations. Xiao et al. reported that ingestion of contaminated tea poses human exposure risks to NEO residues, yet empirical research on this topic is limited [32]. Xiao et al. collected 220 tea samples (unfermented green, semi-fermented white/oolong, fully fermented black, post-fermented dark) from four Chinese regions [32]. Wang et al. developed a quantum-dot-based fluorescent lateral flow immunochromatographic strip (LFICS) coupled with a broad-specific antibody for detecting three typical NEOs (IMI, IMZ, CLO) [33].

2.3.3 Animals

NEOs accumulate in terrestrial and aquatic animals through dietary intake or water exposure. Birds are exposed to NEOs not only *via* direct ingestion of coated

seeds and NEO-containing plant material, but it is now also clear that NEOs dissolve in water and soil – causing long-lasting, intensive pollution across large continental scales [34]. While NEOs' half-lives are typically short, the time required for the most widely used NEOs to degrade to half their original amount (i.e., DT50 or half-life) ranges from 4.7 to 40.3 days in water and 3 to >1,000 days in soil [35]. NEOs accumulate in birds – including upper trophic level species such as birds of prey and owls [36]. Molenaar et al. systematically quantified, *via* an extensive meta-analytic model of experimental exposure studies, which key performance metrics (health, behavior, reproduction, survival) are affected by direct NEO exposure [37].

The neonicotinoid IMI, when extensively used, causes unintended toxicity to non-target aquatic fish. Topal et al. evaluated its neurotoxicity in rainbow trout by measuring 8-hydroxy-2-deoxyguanosine (8-OHdG) activity, oxidative stress markers, and acetylcholinesterase (AChE) activity in brain tissue after a 21-day exposure to 5, 10, or 20 mg/L IMI [38]. Brain tissue showed significantly higher antioxidant enzyme (SOD, CAT, GPx) activities and malondialdehyde (MDA) levels compared to the control ($p < 0.05$). High IMI concentrations also significantly reduced AChE activity ($p < 0.05$).

2.3.4 Microorganisms

NEOs affect soil and aquatic microbial communities, altering diversity and function. Principal component analysis showed that IMI shifted measured parameters, confirming its risk to soil biochemical and microbial activity [39]. During plant treatment, IMI enters the soil and exhibits high persistence, with a half-life ($t_{1/2}$) of up to 229 days [39]. Its behavior in soil depends on soil physicochemical properties, including organic matter type and content, pH, temperature, IMI concentration, presence of cover crops, and time.

2.4 Food products

Dietary intake is the primary route of human exposure to NEOs, with tea, milk, and grains being major contributors.

Tea infusions: NEOs transfer from tea leaves to infusions during brewing. Xiao et al. found that transfer rates (TRs) were highest in the first brew (30–60%) and declined gradually in subsequent brews [32]. After three brews, the TRs of $\Sigma 6$ NEOs dropped by 40–50%, suggesting that discarding the first two brews can reduce exposure [32]. Green tea infusions had the highest NEOs concentrations (8.76–29.77 ng/mL), followed by oolong tea (6.54–15.30 ng/mL) and black tea (4.47–9.68 ng/mL) [32].

Milk: Since the 1990s, the global application of NEOs has increased dramatically; however, the extent of human exposure to these compounds and their potential health risks remains incompletely unraveled. Wei et al. analyzed residues of 16 NEOs and their metabolites in 205 commercial cow milk samples from China's market [40]. Fedrizzi et al. evaluated five NEOs (ACE, IMI, CLO, THD, TMX) in sheep (37 samples) and cow (31 samples) milk from the Jordan Valley – an area with citrus plantations using these insecticides [41]. The analytical method (diatomaceous earth SPE cleanup + LC–MS/MS) achieved 75.1–88.3% recoveries, 0.5 $\mu\text{g/kg}$ LOD, and 1 $\mu\text{g/kg}$ LOQ (far below Codex milk residue limits) [41].

Grains and cereals: In Shandong and Jiangsu, mean total NEOs concentrations in wheat soils exceeded those in corn soils; in Liaoning, corn soils had higher levels than rice soils. Across all crops, the order was: wheat soil (42.47 ng/g) > corn soil (22.08 ng/g) > rice soil (12.05 ng/g). Compositional analysis showed IMI, CLO, and TMX accounted for 93.6–94.4% (mean: 94.1%), 97.2–100% (mean: 99.5%), and 94.1–99.6% (mean: 97.4%) of total NEOs in rice, corn, and wheat soils, respectively [4]. Carbonell-Rozas et al. reported that separation was achieved in <19 min using a Zorbax XDB-C18 column (150 mm × 0.5 mm i.d., 5 µm) at 25 °C [42].

3. Environmental risks of neonicotinoid insecticides

3.1 Human health risks

Human exposure to NEOs is ubiquitous due to their widespread presence in food, water, and air, with vulnerable populations (neonates, children, pregnant women) facing elevated risks.

3.1.1 Exposure assessment

NEO exposure is quantified *via* estimated daily intake (EDI), hazard quotient (HQ), and biomonitoring (urine, serum, cerebrospinal fluid). Differences in dietary patterns, regional agricultural practices, and physiological status (pregnancy) lead to significant exposure variability.

Children and adolescents: Six NEOs – IMI, TMX, ACE, CLO, THD, DIN – were detected in 305 children's urine samples with high frequencies (>90%), indicating widespread exposure in this population. Their median urinary concentrations were 0.13, 0.21, 0.01, 0.19, 0.002, and 1.64 µg/L, respectively. Among the target NEOs, urinary concentrations of CLO showed a significant positive correlation ($p < 0.05$), suggesting common exposure sources [30].

Pregnant women and neonates: Maternal-fetal transfer of NEOs is a critical exposure pathway. Tang et al. detected NEOs/metabolites in 98.9% of neonatal first urine samples from southern China, with *N*-dm-ACE (median: 0.291 ng/mL) being the dominant metabolite, which was 6-fold higher than in Japanese neonates [11].

Occupational exposure: Farmworkers involved in NEOs seed coating or foliar spraying face high inhalation and dermal exposure. Owing to their broad spectrum and lack of cross-resistance, NEOs account for over 25% of the global pesticide market. They have been widely used in more than 120 countries, with an annual global expenditure of \$1.9 billion [43]. For NEOs/m, *N*-dm-ACE, IMI, and TMX were most frequently detected, with IMI having the highest GM concentration (8.7 µg/g-creatinine) [44].

3.1.2 Health effects

Epidemiological and toxicological studies have linked NEOs exposure to diverse adverse outcomes, with recent research focusing on long-term chronic effects and mechanistic pathways (oxidative stress, endocrine disruption). IMI exposure significantly reduced the number and activity of microglia during development, induced neural circuit dysfunction in the hippocampal CA1 and CA3 regions in the

early post-natal period, and suppressed *csf1r* expression during development [45]. 6-Chloropyridine-3-carboxylic acid (6-CN) showed the highest median concentration (9.58 µg/g creatinine, creatinine-adjusted). A 10-fold increase in IMI ($\beta = -1.83$; 95% CI: $-3.04, -0.62$) and ACE ($\beta = -2.27$; 95% CI: $-3.56, -0.98$) reduced newborn head circumference; a 10-fold higher IMI increased newborn PI ($\beta = 0.40$; 95% CI: $0.03, 0.75$) [46].

Metabolic disorders: NEOs are widely used globally, leading to their extensive environmental distribution and frequent detection in humans. The hazard quotient (HQ) and hazard index (HI) were used to assess exposure risks of individual and combined NNIs *via* vegetable/fruit intake, respectively [47]. Sun et al. investigated IMI's effects and its interaction with dietary fat on adiposity and insulin resistance in male C57BL/6 J mice [48]. IMI altered the expression of genes regulating lipid/glucose metabolism – including those in the AMP-activated protein kinase- α (AMPK α) pathway – in white adipose tissue and liver [48].

Available toxicological data from animal studies indicate potential genotoxicity, cytotoxicity, impaired immune function, and reduced growth and reproductive success, even at low concentrations [34]. Bone biopsies from exposed individuals showed reduced osteoblast activity (lower alkaline phosphatase levels) and increased osteoclast differentiation – effects attributed to NEOs-induced oxidative stress (elevated 8-OHdG levels in serum, $r = 0.41$, $p < 0.01$).

3.2 Ecological risks

3.2.1 Birds

Birds are highly vulnerable to NEOs due to their widespread exposure pathways, including ingestion of NEO-contaminated seeds, insects, or water, and inhalation of NEO-laden dust [8]. Molenaar et al. meta-analyzed 1612 effect sizes from 49 studies, finding that NEOs consistently harm bird health, behavior, reproduction, and survival [37]. Beyond reduced food availability, their direct negative effects likely drive global bird declines. Despite local bans, neonicotinoid metabolites and residues remain in the environment and in birds, with long-lasting direct impacts on individuals and populations [37].

NEOs harm bird physiology; U.S. data links 2008–2014 NEO use to bird biodiversity decline. Accounting for the dynamic effects of population declines on future growth, these rates rose to 12% and 5% annually, respectively [49]. IMI reduced fat stores and mass (mean loss: -17% low, -25% high dose) and disrupted orientation; chlorpyrifos impaired orientation but not mass. Wild songbirds eating 4 IMI-treated canola seeds or 8 chlorpyrifos granules daily for 3 days may face poor condition, migration delays, misorientation, and higher mortality/breeding loss risks [50].

NEOs interfere with bird neurobehavioral functions, including foraging, navigation, and social interaction, by targeting nAChRs in the brain [51]. NEOs are the most widely used insecticides globally. Compared to controls, exposed offspring had lower triglycerides and altered motor/social behaviors (enhanced dominance, reduced depression/aggression). Low IMI levels were found in the maternal brain and liver, with traces detected in some offspring [51].

NEOs damage bird reproductive systems at multiple levels, from hormone regulation to offspring survival. All three caused sub-lethal effects (genotoxicity, impaired immunity, reduced growth/reproduction) at concentrations far below

lethal levels. Seed treatments of IMI/CLO risked small birds – even a few seeds could kill or impair reproduction. Freshwater vertebrates faced no lethal risks from environmental IMI/CLO, but not fipronil (some levels harmed fish) [52]. Environmental samples also contained NEOs, indicating agricultural exposure. Compounds accumulated more in albumin than yolk (albumin-to-yolk ratios: 263–694) [53].

Acute and chronic NEOs exposure increases bird mortality, with effects varying by exposure duration and dose. CLO/TMX affected intake/markers but less severely, with no neurotoxicity observed. Acute exposure harms songbirds, risking survival [54]. The LogRR (logarithm of relative risk) value indicates that exposed birds had a 29% lower survival probability (calculated as $RR = \exp(-0.34) \approx 0.71$) compared to unexposed birds, with effects manifesting within 8 days of initial exposure. Only two (one adult and one nestling from Kern County dairy farm breeding colonies) had detectable CLO (40 ppb and 7 ppb, respectively) [55].

3.2.2 Bees

Bees (honeybees, bumblebees, solitary bees) are critical pollinators, and NEOs exposure, even at sublethal concentrations, disrupts their individual physiology and colony function. Most studies assessed individual bees; linking individual effects to sub-individual mechanisms, colonies, and populations is needed. Finally, future research should clarify NEOs' role relative to other drivers of bee declines [56]. Expressing honeybee CYP3 clade P450s identified CYP9Q3, which efficiently metabolizes THD but not IMI. Bumblebees also differ in neonicotinoid sensitivity; CYP9Q4 (CYP9Q3 ortholog) is their key metabolic determinant [57].

3.2.3 Aquatic organisms

NEOs are highly water-soluble, leading to widespread contamination of surface water and groundwater [5]. Malhotra et al. demonstrated that NEOs are highly toxic to diverse aquatic invertebrates, and field-realistic exposures often yield results distinct from or non-comparable to laboratory exposures [58]. This review addresses NEOs' environmental impacts and proposes policies to mitigate adverse biological and ecological effects on non-target aquatic species – ultimately preventing further harm to aquatic food webs [9].

3.2.4 Microorganisms

Soil microbial communities are critical for nutrient cycling and organic matter decomposition. Pesticides support pest management and agriculture, but overuse harms human health and the environment. NEOs – the most widely used systemic insecticides – raise global concerns over pollinator impacts. Post-application, unabsorbed NEOs accumulate in soil, affecting soil microbes. This review synthesizes lab and field studies, showing NEOs alter soil microbial activity and communities *via* unique chemical properties, soil degradation, soil type, soil property effects, and application methods. NNIs change microbial diversity, structure, and abundance (some groups increase or decrease). *Pseudomonadota*, *Bacillota*, *Actinomycetota*, *Nitrospirata*, and families like *Nitrosomonadaceae* often increase post-exposure [59]. Paichongding (IPP) – a novel cis-nitromethylene NEO

developed in China – inhibited urease activity in the first 75 days of incubation, with this effect weakening afterward [60].

3.2.5 Risk levels

Molecular Level: NEOs interact with nAChRs in insects and mammals, but binding affinity varies by species. In insects, NEOs bind to $\alpha 4\beta 2$ nAChRs with high affinity, causing overstimulation and death [1]. Parent neonicotinoids (p-NEOs) and their metabolites (m-NEOs) were quantified in 95 paired maternal serum (MS) and cord serum (CS) samples from southern China. IMI was the dominant p-NEO in both matrices, with median concentrations of 1.84 ng/mL (CS) and 0.79 ng/mL (MS). *N*-dm-ACE was the most abundant m-NEO, with median concentrations of 0.083 ng/mL (CS) and 0.13 ng/mL (MS). Transplacental transfer efficiencies (TTEs) of p-NEOs and m-NEOs were high (median range: 0.81 for TMX to 1.61 for olefin-IMI (of-IMI)), confirming efficient placental transfer. Additionally, NEOs' transplacental transport is passive and structure-dependent: cyanoamidine NEOs (ACE, THD) had higher TTEs than nitroguanidine NEOs (CLO) [61].

Protein Level: NEOs exposure alters the expression of proteins involved in detoxification, oxidative stress, and neurodevelopment. Sheets et al. collated *in vitro*, *in vivo*, and epidemiological studies, as well as GLP-compliant, EPA-aligned rat studies, focusing on six major market-registered NEOs: IMI, ACE, THD, CLO, TMX, and DIN [62]. For the guideline-based studies, primiparous female rats received treatment (three dose levels + vehicle control; ≥ 20 rats/dose) *via* diet or gavage from gestation day 0 or 6 to lactation day 21. F1 offspring (males/females) were assessed for motor activity, acoustic startle response, cognition, brain morphometry, and neuropathology.

Individual Level: NEOs – systemic insecticides used in agriculture across more than 120 countries – contaminate soil *via* widespread agricultural and veterinary use, with residues further reaching aquatic environments. Recent global monitoring shows these pesticides (residues: ng/L– μ g/L) pollute streams, rivers, and lakes [63]. They pose major environmental risks to non-target species: terrestrial (mammals, birds, reptiles), semiaquatic (amphibians), and aquatic (fish, crabs, shrimps, oysters). Benli detailed NEOs' toxicity to non-target species (fish, amphibians, reptiles), covering their biochemical, physiological, and behavioral responses [63]. Data show short- and long-term exposure causes multi-system toxicity, harming survival, development, and reproduction across life stages.

4. Risk control technologies for neonicotinoid insecticides

4.1 Physicochemical technologies

Physicochemical methods are widely used for NEOs' removal from water and soil, with recent advances focusing on catalyst modification and process integration to improve efficiency and reduce costs.

4.1.1 Adsorption

Adsorption is ideal for low-concentration NEOs removal, with adsorbent material properties (specific surface area, functional groups) determining efficiency. Biochar:

Modified biochar exhibits enhanced adsorption capacity. Cui et al. revealed that the interaction mechanisms between biochar and NEOs primarily involve π - π interactions, electrostatic interactions, pore filling, and hydrogen bonding [64]. Biochar boosts NNI degradation via Fenton, photocatalysis, persulfate oxidation, biodegradation (radical/non-radical processes), as well as biodegradation – predominantly through radical processes (e.g., involving $\text{SO}_4^{\bullet-}$, $\bullet\text{OH}$, and $\bullet\text{O}_2^-$) and non-radical processes (e.g., involving $^1\text{O}_2$ and electron transfer) [64]. Sriksaow et al. applied eucalyptus wood chip-derived biochar (BC) to remove three pesticides (IMI, ACE, methomyl) from water [65]. Pesticide adsorption on BC was best fitted by the pseudo-second-order kinetic model. BC's maximum adsorption capacities were 32.42 mg g^{-1} (methomyl), 14.75 mg g^{-1} (IMI), and 4.87 mg g^{-1} (ACE). Key interactions included π - π bonding and hydrogen bonding; the steric aromatic groups of adsorbed IMI/ACE hindered other pesticide molecules from accessing sorption sites [65].

4.1.2 Catalytic degradation

Advanced oxidation processes (AOPs) generate reactive oxygen species (ROS) to degrade NEOs, with recent progress in metal-free catalysts and pH tolerance. OCN is a metal-free photocatalyst. Tan et al. synthesized OCN-10 (10% oxygen doping) that activated PMS under visible light [13]. IMI is a global concern owing to its wide distribution, persistence, high toxicity, and the limited efficacy of conventional treatment methods. Conventional Fenton (CF) techniques have attracted attention for effectively and eco-friendly degrading IMI, yet they suffer from prolonged treatment times and substantial sludge generation. Wang et al. explored IMI removal from its commercial formulation *via* a combined electro-Fenton (EF)-CF process [66]. The CF-EF process outperformed EF alone: it achieved 80% IMI removal in 80 minutes, 68.6% COD removal in 50 minutes of electrolysis, and a Mineralization Current Efficiency (MCE%) of 1.1%. IMI degradation mainly involves hydroxyl ($\bullet\text{OH}$), singlet oxygen ($^1\text{O}_2$), and superoxide ($\bullet\text{O}_2^-$) radicals, with $\bullet\text{OH}$ being dominant [66]. The apparent first-order rate constant (k_{app}) of $\text{SO}_4\text{-Ag}_3\text{PO}_4$ varied with the type of NEOs, ranging from 0.003 to 0.432 min^{-1} , and was at least 5.4-fold higher than that of pristine Ag_3PO_4 . The degradation rate followed the order: THD > NTP > IMI > CLO > ACE > TMX > DIN [67].

4.2 Biotechnologies

Biotechnologies (microbial degradation, phytoremediation) are environmentally friendly, with recent advances in strain engineering and symbiotic systems.

4.2.1 Microbial degradation

Microorganisms degrade NEOs *via* enzymatic pathways (hydrolysis, oxidation), with strain specificity determining the substrate range. *Pigmentiphaga* sp. AAP-1 is a highly efficient ACE-degrading bacterium [12]. The extensive agricultural use of NEOs (notably THD, THI, TMX, THIA) raises major environmental and ecological concerns. Microbial bioremediation is a promising mitigation strategy, yet while THI/THIA-degrading microorganisms have been identified, their degradation mechanisms remain unclear. Zhao et al. comprehensively examined key catabolic enzymes (nitrile hydratases, NHases; cytochrome P450s, CYPs; aldehyde oxidases, AOXs) and the synergistic potential of microbial communities in enhancing

degradation (especially in complex pesticide-contaminated environments) [68]. The microalgae produced oxygen *via* photosynthesis, enhancing bacterial respiration and enzyme activity. The consortia also reduced wastewater toxicity by 60% (measured *via* a daphnia survival assay), compared to 35% for microalgae alone.

4.2.2 Phytoremediation

Plants remove NEOs *via* absorption and rhizosphere degradation, with recent focus on wetland plants and endophyte symbiosis. McKnight et al. compared three wetland species for IMI removal: *Juncus effusus*, *Pontederia cordata*, and *Sagittaria latifolia* [69]. Plants were destructively harvested at 14, 28, and 56 days after the experiment began, and pesticide residues in soil, above-ground vegetation, and below-ground vegetation were analyzed. Results showed that at 56 days, *Pontederia cordata* achieved a greater reduction in azoxystrobin (51.7% lower than treated non-planted containers) compared to *Juncus effusus* and *Sagittaria latifolia* (24.9% and 28.7% lower than non-planted containers, respectively). In contrast, *S. latifolia* exhibited a more significant reduction in IMI at 56 days (79.3% lower than non-planted containers) than *J. effusus* and *P. cordata* (36.0% and 37.1% lower than non-planted containers, respectively) [69]. Widely used NEOs severely threaten the ecological environment and human health, posing an urgent environmental problem. Li et al. showed that *P. chrysosporium* improved TMX degradation in both non-sterilized and sterilized soils, with obvious bioaugmentation in non-sterilized soil at the early stage (<10 days) [70].

4.2.3 Physicochemically enhanced microbial remediation

Characterized by low volatility, high water solubility, and a long half-life in soil and aquatic environments, NEOs have accumulated significantly in the environment over the past two decades due to their widespread application. This residual buildup has exerted severe adverse effects on non-target organisms, including humans. The degradation of NEOs has garnered widespread attention, as it is crucial for environmental protection and biodiversity conservation. Combining physicochemical methods with microbial remediation enhances NEOs removal. Among various NEOs degradation technologies, biological approaches are widely recognized as cost-effective, eco-friendly, and highly efficient. Notably, microbial species enable more accessible, rapid, and robust degradation of xenobiotics (such as NEOs), largely owing to their small size and high metabolic activity. NEOs are low-volatile, highly soluble, and long-lived in soil and water, with rising environmental residues over two decades harming non-target organisms (including humans) [71]. Biological degradation – especially *via* microbes (small, fast-acting) – is cost-effective, eco-friendly, and efficient, converting NEOs to less toxic substances. Solarization raised soil temperature, while compost provided nutrients for microbial growth.

5. Challenges and future directions

5.1 Analytical detection

Detecting NEOs and their metabolites is challenging due to their low concentrations (ng/L to µg/L), complex matrices (soil, food, biological samples), and

the presence of multiple transformation products. An analytical method was optimized for extracting and determining NEO residues and their metabolites in honey bees and bee products. Samples were extracted with 2% triethylamine (TEA) in acetonitrile (ACN), followed by salting out, solid-phase extraction (SPE) cleanup, and detection *via* liquid chromatography – tandem mass spectrometry (LC-MS/MS). Validated in triplicate at three fortification concentrations per matrix, the method showed good recoveries (70–120%) for most analytes and relative standard deviations <20% in most cases [72]. Limits of detection were 0.2 ng/g for parent NEOs and 0.2–15 ng/g for metabolites. Kamel et al.'s refined method offers lower detection limits and improved recoveries, aiding the evaluation of NEOs' subchronic effects, addressing colony collapse disorder (CCD) data gaps, and clarifying pesticide roles in pollinator decline [72]. Future research should prioritize developing rapid, sensitive, and cost-effective detection tools, such as biosensors and portable HPLC-MS/MS, for on-site monitoring.

5.2 Endocrine disrupting effects

NEOs act as endocrine disruptors by interfering with the hypothalamic–pituitary–adrenal (HPA) axis and thyroid function, but their mechanisms remain poorly understood. Growing evidence indicates NEOs may exert long-term adverse effects on bee health, though the underlying mechanisms remain unclear. Pesticides can act as endocrine-disrupting chemicals (EDCs) in animals, characterized by multiphasic dose-response curves and non-lethal endpoints in toxicity studies – but whether NEOs act as EDCs in bees is unknown [73]. Acute studies revealed late-onset non-lethal symptoms (e.g., ataxia) in all species; CLO and TMX showed biphasic dose-response curves across all three. Notably, CLO and TMX were extremely toxic to winter worker honey bees (pre-spring brood production) – the most sensitive bee stage identified so far. Chronic exposure to field-realistic neonicotinoid levels reduced survival and induced significant late-onset symptoms in all three species. Future studies should investigate the molecular mechanisms of NEO-induced endocrine disruption, including interactions with hormone receptors and regulation of gene expression.

5.3 Toxicity of transformation products

NEOs' transformation products (*N*-dm-ACE, DIN-U) often exhibit higher toxicity than their parent compounds. *N*-dm-ACE is more toxic to honeybees than ACE, and DIN-U shows greater oxidative stress potential than DIN [31]. Neonicotinoid transformation products (t-NEOs) draw significant attention due to their potentially higher environmental persistence and toxicity compared to parent compounds, yet systematic reviews on their human health risks are lacking. This review summarizes t-NEOs' physical properties, transformation patterns, and predicted toxicity, using the PECO framework to optimize exposure assessment. It highlights t-NEOs' distinct toxicity (e.g., hydroxylation boosting mammalian toxicity), dominant human exposure *via* water/food (possibly leading to higher internal levels than p-NEOs), and unique risks (transplacental transfer, enhanced neurotoxicity). It calls for greater focus on t-NEOs under the One-Health perspective [74]. However, little is known about their environmental behavior, transport, and long-term toxicity. Future research must characterize the formation, fate, and

toxicity of these transformation products and integrate them into risk assessment frameworks.

5.4 Integrated control strategies

Single risk control technologies have inherent limitations: adsorption requires regeneration, photocatalysis depends on light availability, and microbial degradation is slow. Integrated strategies, such as adsorption–catalysis (biochar–PMS photocatalysis) and physicochemical–biological combinations (solarization–microbial remediation), show great promise. NEOs are widely used globally, especially in agriculture, but mounting evidence links their large-scale, preventive use to serious risks for beneficial organisms and ecology. This drives exploration of alternatives, exemplified by Italian maize and Canadian forestry under integrated pest management (IPM) – which uses data for need-based decisions. Further research is needed, along with knowledge transfer, training, and policies to boost IPM and alternative adoption [75]. Future work should optimize these integrated technologies for large-scale application, balancing cost, efficiency, and environmental compatibility.

5.5 Policy and regulation

Global regulatory disparities significantly hinder the effective mitigation of NEO risks across regions. NEOs are a widely used insecticide class, partly due to their low acute risk to non-target organisms. Yet, rising concerns over their long-term chronic impacts on pollinators and other key species have driven increased governmental regulations since the mid-2010s, with a particular focus on agricultural settings [76]. As the agricultural regulatory landscape for NEOs evolves rapidly, it is critical to review the contexts shaping diverse regulatory approaches, existing regulatory templates, and the consequences of these measures so far. Objectives focus on deepening comprehension of how agricultural neonicotinoid regulatory frameworks might progress across various regions and over time.

6. Conclusion(s)

NEOs are widely used globally, but their environmental persistence and systemic properties have led to ubiquitous contamination and significant risks to human health and ecosystems. This chapter summarizes NEOs' emission pathways, environmental distribution, and associated risks, while reviewing the latest risk control technologies. NEOs enter the environment through industrial production, agricultural application, and wastewater discharge, and are detected in water, soil, air, biota, and food products. Human exposure *via* dietary intake poses risks to neonates, children, and adults, with links to neurodevelopmental disorders, metabolic diseases, and chronic illnesses. Ecologically, NEOs impair the health of birds, bees, and aquatic organisms, disrupting food webs and ecosystem function. Risk control technologies for NEOs include physicochemical methods (adsorption, photocatalysis, Fenton processes) and biotechnologies (microbial degradation, phytoremediation), each with unique strengths and limitations. Integrated strategies

promise efficient, sustainable NEOs removal but face key challenges: detecting low concentrations/transformants, clarifying endocrine effects, and developing cost-effective large-scale technologies. Future research should focus on characterizing NEOs transformation products, optimizing integrated control strategies, and strengthening policy and regulation to mitigate risks.

Acknowledgments

This work was financially supported by the University-level Natural Science Research Project of Weifang University of Science and Technology (2025XJKJ02), the China National University Student Innovation & Entrepreneurship Development Program (202410429017), and the College Students' Innovative Entrepreneurial Training Plan Program (S202410429108).

Conflict of Interest

The authors declare no conflict of interest.

Author details

Xiaoning Wang¹, Chuanxi Yang^{1*}, Yongkun Wu², Mingfang Zhang², Kaipeng Sun², Yiyong Xu³ and Ziheng Wan⁴

1 Shandong Engineering Research Center of Green and High-Value Marine Fine Chemicals, School of Chemical Engineering and Environment, Weifang University of Science and Technology, Weifang, China

2 School of Environmental and Municipal Engineering, Qingdao University of Technology, Qingdao, China

3 Chinese Research Academy of Environmental Sciences, Beijing, China

4 College of Environmental Science and Engineering, Ocean University of China, Qingdao, China

*Address all correspondence to: yangchuanxi1989@hotmail.com

IntechOpen

© 2025 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Jeschke P, Nauen R, Schindler M, Elbert A. Overview of the status and global strategy for neonicotinoids. *Journal of Agricultural and Food Chemistry*. 2011;**59**(7):2897–2908. DOI: 10.1021/jf101303g
- [2] Bass C, Denholm I, Williamson MS, Nauen R. The global status of insect resistance to neonicotinoid insecticides. *Pesticide Biochemistry and Physiology*. 2015;**121**:78–87. DOI: 10.1016/j.pestbp.2015.04.004
- [3] Simon-Delso N, Amaral-Rogers V, Belzunces LP, Bonmatin JM, Chagnon M, Downs C, Furlan L, Gibbons DW, Giorio C, Girolami V, Goulson D, Kreutzweiser DP, Krupke CH, Liess M, Long E, McField M, Mineau P, Mitchell EAD, Morrissey CA, Noome DA, Pisa L, Settele J, Stark JD, Tapparo A, Van Dyck H, Van Praagh J, Van der Sluijs JP, Whitehorn PR, Wiemers M. Systemic insecticides (neonicotinoids and fipronil): Trends, uses, mode of action and metabolites. *Environmental Science and Pollution Research*. 2015;**22**:5–34. DOI: 10.1007/s11356-014-3470-y
- [4] Wu JX, Yu PZ, Zou ZY, Zhao EC, Jing JJ, Zhang JW, Tao Y, Ren LR, He M, Chen L, Han P. Occurrence and ecological risks of neonicotinoids in wheat, corn and rice field soils in China. *Molecules*. 2025;**30**(8):1803. DOI: 10.3390/molecules30081803
- [5] Millot F, Decors A, Mastain O, Quintaine T, Berny P, Vey D, Lasseur R, Bro E. Field evidence of bird poisonings by imidacloprid-treated seeds: A review of incidents reported by the French SAGIR network from 1995 to 2014. *Environmental Science and Pollution Research*. 2017;**24**:5469–5485. DOI: 10.1007/s11356-016-8272-y
- [6] Batikian CM, Lu A, Watanabe K, Pitt J, Gersberg RM. Temporal pattern in levels of the neonicotinoid insecticide, imidacloprid, in an urban stream. *Chemosphere*. 2019;**223**:83–90. DOI: 10.1016/j.chemosphere.2019.01.165
- [7] Tsvetkov N, Samson-Robert O, Sood K, Patel HS, Malena DA, Gajiwala PH, Maciukiewicz P, Fournier V, Zayed A. Chronic exposure to neonicotinoids reduces honey bee health near corn crops. *Science*. 2017;**356**:1395–1397. DOI: 10.1126/science.aam7470
- [8] Hallmann CA, Foppen RPB, Van Turnhout CAM, De Kroon H, Jongejans E. Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature*. 2014;**511**:341–343. DOI: 10.1038/nature13531
- [9] Yamamuro M, Komuro T, Kamiya H, Kato T, Hasegawa H, Kameda Y. Neonicotinoids disrupt aquatic food webs and decrease fishery yields. *Science*. 2019;**366**(6465):620–623. DOI: 10.1126/science.aax3442
- [10] Vuong AM, Zhang C, Chen AM. Associations of neonicotinoids with insulin and glucose homeostasis parameters in US adults: NHANES 2015-2016. *Chemosphere*. 2022;**286**:131642. DOI: 10.1016/j.chemosphere.2021.131642
- [11] Tang ZX, Su ZW, Jia CH, Wei X, Zhu ZN, Qi YF, Zhang ZY, Yao LJ, Tu HX, Huang XH, Niu QQ, Sun WW,

- Wu HJ, Yin RL, Li AJ, Wu F. Neonicotinoid insecticides and metabolites levels in neonatal first urine from southern China: Exploring links to preterm birth. *Journal of Hazardous Materials*. 2024;**469**:133910. DOI: 10.1016/j.jhazmat.2024.133910
- [12] Wang GL, Yue WL, Liu Y, Li F, Xiong MH, Zhang H. Biodegradation of acetamiprid by *Pigmentiphaga* sp. AAP-1 and characterization of a novel acetamiprid hydrolase. *Bioresource Technology*. 2013;**138**:359–368. DOI: 10.1016/j.biortech.2013.03.193
- [13] Tan J, Li ZF, Li J, Meng Y, Yao XL, Wang YH, Lu Y, Zhang TT. Visible-light-assisted peroxymonosulfate activation by metal-free bifunctional oxygen-doped graphitic carbon nitride for enhanced degradation of imidacloprid: Role of non-photochemical and photocatalytic activation pathway. *Journal of Hazardous Materials*. 2022;**423**:127048. DOI: 10.1016/j.jhazmat.2021.127048
- [14] Casida JE. Neonicotinoid metabolism: Compounds, substituents, pathways, enzymes, organisms, and relevance. *Journal of Agricultural and Food Chemistry*. 2011;**59**(7):2923–2931. DOI: 10.1021/jf102438c
- [15] Zhao YX, Shen Y, Chen LW, Li J, Yang J. Emission pathways and environmental behavior of neonicotinoid insecticides. *Environmental Science: Processes & Impacts*. 2025;**27**(4):818–832. DOI: 10.1039/D4EM00798K
- [16] Anderson JC, Dubetz C, Palace VP. Neonicotinoids in the Canadian aquatic environment: A literature review on current use products with a focus on fate, exposure, and biological effects. *Science of the Total Environment*. 2015;**505**:409–422. DOI: 10.1016/j.scitotenv.2014.09.090
- [17] Goulson D. An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*. 2013;**50**(4):977–987. DOI: 10.1111/1365-2664.12111
- [18] Tapparo A, Marton D, Giorio C, Zanella A, Soldà L, Marzaro M, Vivan L, Girolami V. Assessment of the environmental exposure of honeybees to particulate matter containing neonicotinoid insecticides coming from corn coated seeds. *Environmental Science & Technology*. 2012;**46**(5):2592–2599. DOI: 10.1021/es2035152
- [19] Chen QY, Zhang YY, Su GY. Comparative study of neonicotinoid insecticides (NNIs) and NNI-related substances (r-NNIs) in foodstuffs and indoor dust. *Environment International*. 2022;**166**:107368. DOI: 10.1016/j.envint.2022.107368
- [20] Sadaria AM, Supowit SD, Halden RU. Mass balance assessment for six neonicotinoid insecticides during conventional wastewater and wetland treatment: Nationwide reconnaissance in United States wastewater. *Environmental Science & Technology*. 2016;**50**(12):6199–6206. DOI: 10.1021/acs.est.6b01032
- [21] Zhang C, Yi XH, Chen C, Tian D, Liu HB, Xie LT, Zhu XP, Huang MZ, Ying GG. Contamination of neonicotinoid insecticides in soil-water-sediment systems of the urban and rural areas in a rapidly developing region: Guangzhou, South China. *Environment International*. 2020;**139**:105719. DOI: 10.1016/j.envint.2020.105719
- [22] Zhang SQ, Jiang JQ. The occurrence and distribution of

neonicotinoids in sediments, soil, and other environmental media in China: A review. *Environments*. 2025;**12**(5):150. DOI: 10.3390/environments12050150

[23] Hladik ML, Corsi SR, Kolpin DW, Baldwin AK, Blackwell BR, Cavallin JE. Year-round presence of neonicotinoid insecticides in tributaries to the Great Lakes, USA. *Environmental Pollution*. 2018;**235**:1022–1029. DOI: 10.1016/j.envpol.2018.01.013

[24] Yu ZM, Li XF, Wang SR, Liu LY, Zeng EY. The human and ecological risks of neonicotinoid insecticides in soils of an agricultural zone within the Pearl River Delta, South China. *Environmental Pollution*. 2021;**284**:117358. DOI: 10.1016/j.envpol.2021.117358

[25] Tomizawa M, Casida JE. Neonicotinoid insecticide toxicology: Mechanisms of selective action. *Annual Review of Pharmacology and Toxicology*. 2005;**45**:247–268. DOI: 10.1146/annurev.pharmtox.45.120403.095930

[26] Suchail S, Guez D, Belzunces LP. Characteristics of imidacloprid toxicity in two *Apis mellifera* subspecies. *Environmental Toxicology and Chemistry*. 2000;**19**(7):1901–1095. DOI: 10.1002/etc.5620190726

[27] Li Y, Li YD, Bi GH, Ward TJ, Li L. Adsorption and degradation of neonicotinoid insecticides in agricultural soils. *Environmental Science and Pollution Research*. 2023;**30**:47516–47526. DOI: 10.1007/s11356-023-25671-9

[28] Du HR, Zhu XL, Yao YY, Yao W. Occurrence and inhalation health risk of neonicotinoid pesticides in outdoor air particulate matters from 2019 to 2021 in

China. *Environmental Systems Research*. 2024;**13**:18. DOI: 10.1186/s40068-024-00342-x

[29] Harada KH, Tanaka K, Sakamoto H, Imanaka M, Niisoe T, Hitomi T, Kobayashi H, Okuda H, Inoue S, Kusakawa K, Oshima M, Watanabe K, Yasojima M, Takasuga T, Koizumi A. Biological monitoring of human exposure to neonicotinoids using urine samples, and neonicotinoid excretion kinetics. *PLoS One*. 2016;**11**(1):e0146335. DOI: 10.1371/journal.pone.0146335

[30] Zhao Y, Zhu Z, Xiao QR, Li ZH, Jia XH, Hu WT, Liu KC, Lu SY. Urinary neonicotinoid insecticides in children from South China: Concentrations, profiles and influencing factors. *Chemosphere*. 2022;**291**:132937. DOI: 10.1016/j.chemosphere.2021.132937

[31] Yao YN, Song SM, Huang YY, Kannan K, Sun HW, Zhang T. Insights into free and conjugated forms of neonicotinoid insecticides in human serum and their association with oxidative stress. *Environment & Health*. 2023;**1**(2):121–129. DOI: 10.1021/envhealth.3c00023

[32] Xiao QR, Li XY, Xu SY, Chen X, Xu Y, Lu Y, Liu LY, Lin LY, Ma HM, Lu SY. Neonicotinoids in tea leaves and infusions from China: Implications for human exposure. *Science of the Total Environment*. 2023;**905**:166114. DOI: 10.1016/j.scitotenv.2023.166114

[33] Wang SJ, Liu Y, Jiao SS, Zhao Y, Guo YR, Wang MC, Zhu GN. Quantum-dot-based lateral flow immunoassay for detection of neonicotinoid residues in tea leaves. *Journal of Agricultural and Food Chemistry*. 2017;**65**(46):10107–10114. DOI: 10.1021/acs.jafc.7b03981

- [34] Thompson DA, Lehmler HJ, Kolpin DW, Hladik ML, Vargo JD, Schilling KE, LeFevre GH, Peeples TL, Poch MC, LaDuca LE, Cwiertny DM, Field RW. A critical review on the potential impacts of neonicotinoid insecticide use: Current knowledge of environmental fate, toxicity, and implications for human health. *Environmental Science: Processes & Impacts*. 2020;**22**(6):1315–1346. DOI: 10.1039/C9EM00586B
- [35] Hladik ML, Main AR, Goulson D. Environmental risks and challenges associated with neonicotinoid insecticides. *Environmental Science & Technology*. 2018;**52**(6):3329–3335. DOI: 10.1021/acs.est.7b06388
- [36] Humann-Guillemot S, Laurent S, Bize P, Roulin A, Glauser G, Helfenstein F. Contamination by neonicotinoid insecticides in barn owls (*Tyto alba*) and alpine swifts (*Tachymarptis melba*). *Science of the Total Environment*. 2021;**785**:147403. DOI: 10.1016/j.scitotenv.2021.147403
- [37] Molenaar E, Viechtbauer W, van de Crommenacker J, Kingma SA. Neonicotinoids impact all aspects of bird life: A meta-analysis. *Ecology Letters*. 2024;**27**(10):e14534. DOI: 10.1111/ele.14534
- [38] Topal A, Alak G, Ozkaraca M, Yeltekin AC, Comaklı S, Acil G, Kokturk M, Atamanalp M. Neurotoxic responses in brain tissues of rainbow trout exposed to imidacloprid pesticide: Assessment of 8-hydroxy-2-deoxyguanosine activity, oxidative stress and acetylcholinesterase activity. *Chemosphere*. 2017;**175**:186–191. DOI: 10.1016/j.chemosphere.2017.02.047
- [39] Cycoń M, Piotrowska-Seget Z. Biochemical and microbial soil functioning after application of the insecticide imidacloprid. *Journal of Environmental Sciences*. 2015;**27**: 147–158. DOI: 10.1016/j.jes.2014.05.034
- [40] Wei X, Pan YN, Tang ZX, Lin QQ, Jiang YQ, Chen JY, Xian WX, Yin RL, Li AJ, Qiu RL. Neonicotinoids residues in cow milk and health risks to the Chinese general population. *Journal of Hazardous Materials*. 2023;**452**:131296. DOI: 10.1016/j.jhazmat.2023.131296
- [41] Fedrizzi G, Altafini A, Armorini S, Al-Qudah KM, Roncada P. LC–MS/MS analysis of five neonicotinoid pesticides in sheep and cow milk samples collected in Jordan Valley. *Bulletin of Environmental Contamination and Toxicology*. 2019;**102**:347–352. DOI: 10.1007/s00128-019-02555-8
- [42] Carbonell-Rozas L, Lara FJ, Del Olmo Iruela M, García-Campaña AM. A novel approach based on capillary liquid chromatography for the simultaneous determination of neonicotinoid residues in cereal samples. *Microchemical Journal*. 2021;**161**:105756. DOI: 10.1016/j.microc.2020.105756
- [43] Sánchez-Bayo F. The trouble with neonicotinoids. *Science*. 2014;**346** (6211):806–807. DOI: 10.1126/science.1259159
- [44] Suwannarin N, Prapamontol T, Isobe T, Nishihama Y, Nakayama SF. Characteristics of exposure of reproductive-age farmworkers in Chiang Mai Province, Thailand, to organophosphate and neonicotinoid insecticides: A pilot study. *International Journal of Environmental Research and Public Health*. 2020;**17**(21):7871. DOI: 10.3390/ijerph17217871

- [45] Namba K, Tominaga T, Ishihara Y. Decreases in the number of microglia and neural circuit dysfunction elicited by developmental exposure to neonicotinoid pesticides in mice. *Environmental Toxicology*. 2024;**39**(7):3944–3955. DOI: 10.1002/tox.24263
- [46] Pan CY, Yu JX, Yao Q, Lin N, Lu ZP, Zhang Y, Zhao SS, Wang ZX, Lei XN, Tian Y, Gao Y. Prenatal neonicotinoid insecticides exposure, oxidative stress, and birth outcomes. *Environment International*. 2022;**163**:107180. DOI: 10.1016/j.envint.2022.107180
- [47] Wang LL, Ma CC, Wei DD, Wang M, Xu QQ, Wang J, Song Y, Huo WQ, Jing T, Wang CJ, Mao ZX. Health risks of neonicotinoids chronic exposure and its association with glucose metabolism: A case-control study in rural China. *Environmental Pollution*. 2023;**334**:122213. DOI: 10.1016/j.envpol.2023.122213
- [48] Sun QC, Xiao X, Kim Y, Kim D, Yoon KS, Clark JM, Park Y. Imidacloprid promotes high fat diet-induced adiposity and insulin resistance in male C57BL/6J mice. *Journal of Agricultural and Food Chemistry*. 2016;**64**(49):9293–9306. DOI: 10.1021/acs.jafc.6b04322
- [49] Li YJ, Miao RQ, Khanna M. Neonicotinoids and decline in bird biodiversity in the United States. *Nature Sustainability*. 2020;**3**:1027–1035. DOI: 10.1038/s41893-020-0582-x
- [50] Eng ML, Stutchbury BJM, Morrissey CA. Imidacloprid and chlorpyrifos insecticides impair migratory ability in a seed-eating songbird. *Scientific Reports*. 2017;**7**:15176. DOI: 10.1038/s41598-017-15446-x
- [51] Burke AP, Niibori Y, Terayama H, Ito M, Pidgeon C, Arsenault J, Camarero PR, Cummins CL, Mateo R, Sakabe K, Hampson DR. Mammalian susceptibility to a neonicotinoid insecticide after fetal and early postnatal exposure. *Scientific Reports*. 2018;**8**:16639. DOI: 10.1038/s41598-018-35129-5
- [52] Gibbons D, Morrissey C, Mineau P. A review of the direct and indirect effects of neonicotinoids and fipronil on vertebrate wildlife. *Environmental Science and Pollution Research*. 2015;**22**:103–118. DOI: 10.1007/s11356-014-3180-5
- [53] Nimako C, Khidkhan K, Kulprasertsri S, Poapolathep S, Khunlert P, Yohannes YB, Ikenaka Y, Nakayama SMM, Ishizuka M, Poapolathep A. Pollution and partitioning of neonicotinoid insecticides in free-grazing ducks and their eggs: Implications for human health. *Environmental Pollution*. 2025;**373**(15):126099. DOI: 10.1016/j.envpol.2025.126099
- [54] Eng ML, Morrissey CA. Comparative sublethal toxicity of three neonicotinoids in red-winged blackbirds. *Environmental Science & Technology*. 2025;**59**(28):14268–14278. DOI: 10.1021/acs.est.5c03152
- [55] Graves EE, Meese RJ, Holyoak M. Neonicotinoid exposure in Tricolored Blackbirds (*Agelaius tricolor*). *Environmental Science and Pollution Research*. 2023;**30**:15392–15399. DOI: 10.1007/s11356-022-23290-4
- [56] Lundin O, Rundlöf M, Smith HG, Fries I, Bommarco R. Neonicotinoid insecticides and their impacts on bees: A systematic review of research approaches and identification of

- knowledge gaps. *PLoS One*. 2015;**10**(8): e0136928. DOI: 10.1371/journal.pone.0136928
- [57] Manjon C, Troczka BJ, Zaworra M, Beadle K, Randall E, Hertlein G, Singh KS, Zimmer CT, Homem RA, Lueke B, Reid R, Kor L, Kohler M, Benting J, Williamson MS, Davies TGE, Field LM, Bass C, Nauen R. Unravelling the molecular determinants of bee sensitivity to neonicotinoid insecticides. *Current Biology*. 2018;**28**(7):1137–1143. DOI: 10.1016/j.cub.2018.02.045
- [58] Malhotra N, Chen KHC, Huang JC, Lai HT, Uapipatanakul B, Roldan MJM, Macabeo APG, Ger TR, Hsiao CD. Physiological effects of neonicotinoid insecticides on non-target aquatic animals—an updated review. *International Journal of Molecular Sciences*. 2021;**22**(17):9591. DOI: 10.3390/ijms22179591
- [59] Briceño G, Diez MC, Palma G, Jorquera M, Schalchli H, Saez JM, Benimeli CS. Neonicotinoid effects on soil microorganisms: Responses and mitigation strategies. *Sustainability*. 2024;**16**(9):3769. DOI: 10.3390/su16093769
- [60] Cai ZQ, Rong Y, Chen J, Wang J, Ma JT, Zhang WJ, Zhao XY. Effects of the novel *cis*-nitromethylene neonicotinoid insecticide Paichongding on enzyme activities and microorganisms in yellow loam and Huangshi soils. *Environmental Science and Pollution Research*. 2016;**23**: 7786–7793. DOI: 10.1007/s11356-015-6036-8
- [61] Zhang HL, Bai XY, Zhang T, Song SM, Zhu HK, Lu SY, Kannan K, Sun HW. Neonicotinoid insecticides and their metabolites can pass through the human placenta unimpeded. *Environmental Science & Technology*. 2022;**56**(23):17143–17152. DOI: 10.1021/acs.est.2c06091
- [62] Sheets LP, Li AA, Minnema DJ, Collier RH, Creek MR, Pepper RC. A critical review of neonicotinoid insecticides for developmental neurotoxicity. *Critical Reviews in Toxicology*. 2016;**46**(2):153–190. DOI: 10.3109/10408444.2015.1090948
- [63] Benli PP. Responses of fishes, amphibians, and reptiles to neonicotinoids. *Neonicotinoids in the Environment*. 2024;75–90. DOI: 10.1007/978-3-031-45343-4_6
- [64] Cui S, Lv JL, Hough R, Fu Q, An LH, Zhang ZL, Ke YX, Liu ZK, Li YF. Recent advances and prospects of neonicotinoid insecticides removal from aquatic environments using biochar: Adsorption and degradation mechanisms. *Science of the Total Environment*. 2024;**939**:173509. DOI: 10.1016/j.scitotenv.2024.173509
- [65] Sriksaow A, Chaengsawang W, Kiatsiriroat T, Kajitvichyanukul P, Smith SM. Adsorption kinetics of imidacloprid, acetamiprid and methomyl pesticides in aqueous solution onto eucalyptus woodchip derived biochar. *Minerals*. 2022;**12** (5):528. DOI: 10.3390/min12050528
- [66] Wang JZ, Ha TH, Chiemchaisri C, Lu MC. Application of electro-Fenton technology for the degradation of imidacloprid from pesticide wastewater. *Journal of Water Process Engineering*. 2024;**63**:105504. DOI: 10.1016/j.jwpe.2024.105504
- [67] Lee YJ, Kang JK, Park SJ, Lee CG, Moon JK, Alvarez PJJ. Photocatalytic degradation of neonicotinoid insecticides using sulfate-doped Ag₃PO₄

with enhanced visible light activity. *Chemical Engineering Journal*. 2020;**402**:126183. DOI: 10.1016/j.cej.2020.126183

[68] Zhao YX, Chen LW, Shen Y, Chen H, Yu ZY, Xing C, Chen YF, Zhai PF, Song JW, Yang J. Biodegradation of neonicotinoid insecticides thiacloprid and thiamethoxam by microorganisms: Metabolic process, metabolic enzymes and toxicity assessments of their metabolites. *Current Microbiology*. 2025;**82**:347. DOI: 10.1007/s00284-025-04326-7

[69] McKnight AM, Gannon TW, Yelverton F. Phytoremediation of azoxystrobin and imidacloprid by wetland plant species *Juncus effusus*. *Pontederia Cordata* and *Sagittaria Latifolia*. *International Journal of Phytoremediation*. 2022;**24**(2):196–204. DOI: 10.1080/15226514.2021.1932726

[70] Li WJ, Chen AW, Shang C, Zhang XX, Chai YZ, Luo S, Shao JH, Peng L. Remediation of thiamethoxam contaminated wetland soil by *Phanerochaete chrysosporium* and the response of microorganisms. *Journal of Environmental Chemical Engineering*. 2022;**10**(5):108333. DOI: 10.1016/j.jece.2022.108333

[71] Ahmad S, Cui DM, Zhong GH, Liu J. Microbial technologies employed for biodegradation of neonicotinoids in the agroecosystem. *Frontiers in Microbiology*. 2021;**12**:759439. DOI: 10.3389/fmicb.2021.759439

[72] Kamel A. Refined methodology for the determination of neonicotinoid pesticides and their metabolites in honey bees and bee products by liquid chromatography–tandem mass spectrometry (LC-MS/MS). *Journal of*

Agricultural and Food Chemistry. 2010;**58**(10):5926–5931. DOI: 10.1021/jf904120n

[73] Baines D, Wilton E, Pawluk A, de Gorter M, Chomistek N. Neonicotinoids act like endocrine disrupting chemicals in newly-emerged bees and winter bees. *Scientific Reports*. 2017;**7**:10979. DOI: 10.1038/s41598-017-10489-6

[74] Zhang JY, Song SM, He L, Li AJ, You J, Zhang T. Transformation products of neonicotinoids: A review of human exposure, toxicity, and health risks. *Environmental Science & Technology*. 2025;**59**(34):17933–17951. DOI: 10.1021/acs.est.5c00372

[75] Furlan L, Kreutzweiser D. Alternatives to neonicotinoid insecticides for pest control: Case studies in agriculture and forestry. *Environmental Science and Pollution Research*. 2015;**22**:135–147. DOI: 10.1007/s11356-014-3628-7

[76] Dentzman K, Franklin D, Avemegah E, Goldberger JR. An overview of agricultural neonicotinoid regulation in the EU, Canada, and the United States. *Pest Management Science*. 2025;**81**(12):7593–7601. DOI: 10.1002/ps.70126

Edited by Farzana Khan Perveen

This book describes that a pesticide is a substance used to control organisms considered harmful. Pesticides target insect pests, fungi, weeds, and parasitic worms, respectively. Modern agriculture faces a critical dichotomy: the imperative for global food security versus the ecological debt incurred by the inefficiency of conventional agrochemicals. This book explores the 'Nano-Green Nexus', a paradigm shift moving from recalcitrant synthetics to biodegradable, nanotechnology-enabled delivery systems. The agriculture sector is one of the largest users of various synthetic (chemical) insecticides. However, extensive use of synthetic (chemical) insecticides has raised significant concerns, including environmental pollution, harm to non-target organisms, the development of pest resistance, and potential health risks to humans. Botanical insecticides, pest control products derived from plants, have become an important environmentally friendly alternative to synthetic (chemical) insecticides. In addition to their environmentally friendly nature, botanical insecticides offer benefits like low toxicity to non-target organisms, biodegradability, and reduced risk of pest resistance. The agriculture sector plays a pivotal role in ensuring food security and contributing to economic stability. Despite its advantages, the widespread use of synthetic pesticides for pest control poses significant threats to human health, environmental quality, and biological control agents. This book highlights the dual nature of pesticides, focusing on their benefits in enhancing crop yields and their adverse impacts on non-target species. Neonicotinoid insecticides (NEOs) have become the most widely used class of insecticides globally since the 1990s, owing to their high insecticidal efficacy, broad spectrum, and low acute toxicity to mammals. However, their widespread application, high water solubility, environmental persistence, and systemic properties have led to ubiquitous contamination in various environmental media, biota, and food products. This book systematically reviews the emission pathways, environmental distribution, and ecological and human health risks associated with NEOs, and summarizes the latest advances in risk-control technologies.

W. James Grichar, Agricultural Sciences Series Editor

Published in London, UK

© 2026 IntechOpen
© Irena Carpaccio / unsplash

IntechOpen

ISSN 3029-052X

ISBN 978-1-80631-266-5

