Babafemi Raphael Babaniyi
Ebunoluwa Elizabeth Babaniyi *Editors*

The Interplay of Pesticides and Climate Change

Environmental Dynamics and Challenges

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Foreword

The global environmental landscape is undergoing profound transformations, with climate change at the forefront of challenges confronting ecosystems and human societies. At the same time, the widespread use of pesticides has been both a vital tool for agricultural productivity and a source of environmental and health concerns. *The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges* provides a timely and crucial examination of how these two forces—pesticides and climate change—interact to shape our environment, food systems, and future sustainability.

In the first section, the book offers an in-depth introduction to pesticides, explaining their various categories, such as insecticides, herbicides, fungicides, and more specialized compounds. It goes beyond a simple classification to explore the specific environmental impacts of each type, including their potential to disrupt ecosystems, non-target species, and food chains. As readers navigate this section, they will not only gain a clearer understanding of how different pesticides are designed to function but also how they can contribute to unintended consequences when persistent in the environment.

A critical component of the book is its exploration of environmental persistence—the longevity of pesticides and their metabolites in soil, water, and air. With climate change altering precipitation patterns and hydrological cycles, the dynamics of pesticide runoff and leaching become increasingly unpredictable. The book thoughtfully examines how shifting environmental conditions enhance the potential for pesticide residues to persist and accumulate, affecting water quality, aquatic ecosystems, and even human health.

An important and often overlooked aspect is the role of adjuvants, substances added to pesticide formulations to enhance their effectiveness. The book investigates the types of adjuvants used in modern agriculture and their ecological consequences, particularly in the context of climate-induced environmental stress. This nuanced discussion highlights the need to consider not only the active ingredients of pesticides but also the auxiliary chemicals that influence their behavior in natural systems. One of the most significant challenges posed by the dual forces of pesticide use and climate change is how ecosystems respond to these combined stressors. The book presents a thorough analysis of how climate change exacerbates the effects of pesticide exposure, leading to potential declines in biodiversity, altered ecosystem functions, and compromised ecosystem services. However, it also presents strategies to build ecosystem resilience, offering hope for mitigating these negative impacts through adaptive management practices. Another major theme is the impact of pesticide runoff on water quality, a topic that is becoming increasingly relevant as climate change alters weather patterns, increasing the frequency of heavy rainfall events and affecting water availability. The book delves into the cascading effects of pesticide runoff, drift, and leaching into water bodies, underscoring the far-reaching consequences for aquatic ecosystems, drinking water sources, and overall ecosystem health.

Global trade further complicates the picture, as international supply chains and pesticide use patterns are influenced by both economic and environmental factors. This section uncovers how global commerce, intertwined with shifting climatic conditions, can drive pesticide demand in some regions and create cross-border environmental impacts in others. Through this lens, the book calls for collaborative international efforts to tackle the intertwined challenges of pesticide use and climate change. The intricate dynamics between pesticides and climate change are also explored through feedback loops. As climate change alters pest populations, the need for and effectiveness of pesticides evolve, creating cycles that can intensify the very conditions they are meant to control. Additionally, the book highlights how pesticide production, transport, and application contribute to greenhouse gas emissions, linking their use directly to the broader climate crisis.

The book also examines the ecotoxicological effects of pesticides, providing a comprehensive analysis of the direct and indirect impacts on non-target species, including pollinators, beneficial insects, and wildlife. As climate change modifies habitats and species behavior, the combined stress of pesticide exposure may amplify the threats to biodiversity, which in turn affects ecosystem resilience and food security. Through detailed case studies and examples, the book explores the mechanisms by which pesticides disrupt biological systems and offers mitigation strategies that emphasize the protection of biodiversity and ecosystem services.

In response to these challenges, the book investigates technological innovations aimed at reducing the environmental impact of pesticides and improving agricultural resilience to climate change. Emerging solutions such as precision agriculture, remote sensing, and ecofriendly pest control methods—including integrated pest management (IPM) and the development of biopesticides—are discussed as promising alternatives to conventional chemical-based agriculture. These innovations present a pathway toward more sustainable farming practices, with the potential to reduce the environmental footprint of pesticides. Another key focus is the impact of pesticides on soil health and its role in carbon sequestration. The book carefully explores how pesticides influence soil microbial communities, nutrient cycling, and the ability of soils to sequester carbon—a critical function in mitigating climate change. It presents strategies for enhancing soil resilience, including the promotion of sustainable farming techniques that protect soil health and improve its capacity to store carbon. However, the complexity of pesticide and climate change interactions goes beyond the field, extending to human health and community vulnerability. The book takes a close look at the disproportionate impacts on marginalized populations, particularly agricultural workers, indigenous groups, and low-income communities who are often most exposed to both pesticide residues and the effects of climate change. In addressing these inequities, the book offers strategies for enhancing community resilience and advancing environmental justice.

Finally, the book emphasizes the importance of public perception, education, and policy integration in shaping the future of pesticide use and climate action. It calls for greater awareness and engagement among farmers, policymakers, consumers, and researchers in adopting sustainable practices and promoting environmental stewardship. Through collaborative efforts between governments, industry, and civil society, the book envisions a future where the use of pesticides is better managed, environmental impacts are minimized, and agricultural systems are made more resilient to the changing climate.

The editors have done a great job by inviting 71 experienced experts from 9 different countries to contribute to this volume. Therefore, as you journey through the pages of this book, you will gain not only a deep understanding of the scientific and environmental issues at play but also an appreciation for the complex, interconnected solutions needed to address these global challenges. *The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges* is a clarion call for action, offering both the knowledge and the tools necessary to chart a more sustainable path forward for our planet.

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Preface

The world currently confronts unprecedented environmental challenges, with pesticide use and climate change emerging as critical issues that have profound implications. Although these phenomena originate from different sources, they are intricately linked in their effects on ecosystems, agriculture, and human health. The escalating demand for food security has led to the extensive application of pesticides, while climate change disrupts weather patterns and ecosystems, consequently affecting the efficacy of these chemicals. This intricate relationship necessitates thorough analysis and informed action.

The Interplay of Pesticides and Climate Change: Environmental Dynamics and Challenges aims to investigate the synergies and conflicts between pesticide use and climate change. It delves into how changing environmental conditions—such as rising temperatures, altered precipitation patterns, and shifting ecosystems—impact the persistence, behavior, and consequences of pesticides. Additionally, the book explores how these interactions affect agricultural productivity and environmental sustainability, presenting significant challenges to food security, biodiversity, and public health. Through a comprehensive examination of scientific research, case studies, and policy frameworks, this work provides a nuanced understanding of the complexities involved.

Moreover, the book emphasizes the urgent need for adaptive management strategies, regulatory reforms, and innovative agricultural practices that mitigate the adverse effects of pesticides while bolstering resilience against climate impacts.

This publication is designed for researchers, environmental scientists, policymakers, and all individuals concerned about the future of agriculture and environmental stewardship. By bridging two of the most pressing environmental issues of our time, it aspires to promote a more integrated approach to sustainable development and environmental protection.

We hope this book will inspire deeper reflection, foster interdisciplinary collaboration, and motivate action toward addressing the environmental dynamics shaped by the intersection of pesticides and climate change.

Ogbomoso, Nigeria — Babafemi Raphael Babaniyi
Ondo, Nigeria — Ebunoluwa Elizabeth Babaniyi

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We are equally grateful to the reviewers for their thoughtful and invaluable feedback, which significantly contributed to improving the clarity and rigor of the content. Special thanks go to the Springer Editorial and Production team for their unwavering support, professionalism, and seamless collaboration throughout this endeavor. Their commitment to excellence ensured the project reached its full potential.

Ogbomoso, Nigeria — Babafemi Raphael Babaniyi
Ondo, Nigeria — Ebunoluwa Elizabeth Babaniyi

Contents

Part I Pesticides Overview

An Insight to Pesticides 3
Taiwo Hamidat Olaide, Babafemi Raphael Babaniyi, Taiwo Habib Adejumo, Kehinde Oluwasiji Olorunfemi, Olusola David Ogundele, and Olumide Akinrinola

Adjuvants: Types of Adjuvants and Their Effects on Ecosystems in Relation to Climate Change 31
Barbara Sawicka, Piotr Pszczółkowski, Piotr Barbaś, and Barbara Krochmal-Marczak

Resilience of Ecosystems: Navigating the Challenges of Pesticide Exposure and Climate Change 65
Mukul Machhindra Barwant, Shreya Singh, Shivendra Singh, B. Sri Sai Siddartha Naik, and Odangowei Inetiminebi Ogidi

Pesticide Runoff and Its Impact on Water Quality 85
Sayed Rashad, Ghadir A. El-Chaghaby, and Muhammad Abdul Moneem

Global Trade and Pesticide Use 111
Alia Syafiqah Abdul Hamed and Nur Hidayah

Part II Dynamics

Pesticides and Climate Change Feedback Loop 129
Katherine Georgina Menon, Kondakindi Venkateshwar Reddy, B. H. Boje Gowd, P. Paul Vijay, and Routhu Jhansi

Climate Change and Pesticide Dynamics 149
Mukul Machhindra Barwant, Odangowei Inetiminebi Ogidi, Balwant Singh, Varsha Sadashiv Patil, and Shalagha A. B. Sharma

Pesticide Contributions to Greenhouse Gas Emissions 173
Gabriel Gbenga Babaniyi, Ulelu Jessica Akor,
and Abdulhameed Adewale Odeseye

Ecotoxicological Impacts of Pesticide 231
Ojo Emmanuel Ige, Folorunso Patrick Aliu, Adesuyi Emmanuel Omole,
and Oluwaseun Omotayo Alabi

Technological Innovations Aimed at Reducing the Environmental Impact of Pesticides and Increasing the Resilience of Agriculture to Climate Change 253
Barbara Sawicka, Piotr Barbaś, Piotr Pszczółkowski,
and Barbara Krochmal-Marczak

Synergies Between Green Chemistry Principles and the Sustainable Development Goals (SDGs) in Developing Eco-Friendly Pesticides 291
Rodrigo Duarte-Casar, Juan Carlos Romero-Benavides,
Natalia Bailon-Moscoso, Marell Navarro-Rojas,
and Marlene Rojas-Le-Fort

Part III Challenges

The Nexus Between Pesticides, Climate Change, Carbon Sequestration, and Soil Health 315
V. Mageshwaran, O. T. Lawal, O. O. Osemwegie, R. Arutselvan,
and A. F. Ologundudu

Pesticides and Microbiome Shifts 345
Uchechukwu Chinwe Nebo, Amarachi Nchekwube Ugwuja,
Ayoigbala Monioluwa Lawal, and Stanley Ozoemena Agbo

Emerging Pests and Disease Vectors 363
Prity Das, Rakesh Das, Manish Kumar Gautam, and Sandip Mondal

Dynamic Shift in Plant Biodiversity by Herbicides Application 399
Oni Ayodeji Christopher, Daramola Oluwatosin Olaoluwa,
Ewuola Akinola Ayoola, and Aliu Folorunso Patrick

Immedicable Effects of Organic Pesticides on Aquatic Environment . . 421
Mukul Machhindra Barwant, Shalagha A. B. Sharma, Debasree Lodh,
Dipanwita Chaudhuri Sil, and Odangowei Inetiminebi Ogidi

Part IV Strategies for Sustainable Practice

Community Health and Vulnerability 443
Mustapha Abdulsalam, Musa Ojeba Innocent, Miracle Uwa Livinus,
Abdulhakeem Idris Abdulhakeem, Fatimoh Abdulsalam Danjuma,
Abdulsalam Khadijah, Tijani Abiola Tajudeen,
Alege Abdulraheem Lateefat, Idowu Afeez Temitope,
and Ishola Jonathan Adekunle

Study of Consumers Choices on Pesticides Use and Sustainability 469
Mukul Machhindra Barwant, Odangowei Inetiminebi Ogidi,
Channe Yogita, and Rupali Munje

Economic Implications of Climate Change and Pesticide Use on Agriculture 517
Mukul Machhindra Barwant, Shreya Singh,
Odangowei Inetiminebi Ogidi, Shivendra Singh,
and B. Sri Sai Siddartha Naik

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Registration Council of Nigeria (TRCN) since 2019, Ebunoluwa has accumulated significant experience in the field of education. Her contributions are further evidenced by her published research manuscripts, which reflect her commitment to advancing knowledge in her area of expertise.

Part I
Pesticides Overview

This part addresses the multifaceted realm of pesticides, wherein it scrutinizes a plethora of classifications such as insecticides, herbicides, and fungicides.

An Insight to Pesticides

Taiwo Hamidat Olaide, Babafemi Raphael Babaniyi, Taiwo Habib Adejumo, Kehinde Oluwasiji Olorunfemi, Olusola David Ogundele, and Olumide Akinrinola

1 Introduction

Environmental pollution has become a global issue, raising serious concerns about its harmful effects on human health and the stability of ecosystems (Khan et al., 2010; Nasrollahi et al., 2020). Although pollution largely stems from human activities, it is essential to weigh the associated benefits and risks rather than place blame outright (Ahmad et al., 2024; Mahmood et al., 2015). Pesticides, commonly used in agriculture to control pests, insects, and weeds, play a crucial role in both modern farming and health practices (Carvalho, 2017; Mahmood et al., 2015; Umetsu & Shirai, 2020). Each year, around 3 billion kilograms of pesticides is utilized worldwide, with an estimated cost of approximately 40 billion USD (Zhang et al., 2011). Various types of pesticides—including herbicides, insecticides, fungicides, and nematicides—are used extensively to boost crop yields, minimize harvest losses, and increase food supplies. However, the widespread and often unregulated use of these chemicals has led to significant environmental harm and negative health effects. These substances can accumulate in ecosystems, disrupting natural balances through bioaccumulation (Mahmood et al., 2015; Sharma et al., 2019). Due to their non-biodegradable nature, they persist in the environment for prolonged periods,

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presenting considerable biohazards (van Dijk, 2010; Hashimi et al., 2020). The modern surge in chemical use has had a profound impact on the biosphere, affecting life quality (Pimentel, 2005). A wide array of chemical agents is used to control unwanted plant and insect species, with examples like dichloro-diphenyl-trichloroethane (DDT) and its metabolite dichlorodiphenyldichloroethylene (DDE) serving to manage vector-borne diseases such as malaria, dengue (WHO, 2012), leishmaniasis (Claborn, 2010), Japanese encephalitis (JE) (Simon et al., 2024), and schistosomiasis (Schmolke et al., 2010). Epidemiological research has shown that pesticide exposure can harm several organs, including the liver, brain, lungs, and colon. Studies have also linked pesticides to severe diseases like cancer, as they generate reactive oxygen species (ROS) that decrease antioxidant levels and weaken the body's defenses against cellular oxidative damage. Lipids, proteins, and nucleic acids are especially vulnerable to this oxidative imbalance, which interferes with cellular signaling and may cause chronic health issues, including reproductive disorders in both humans and animals (Ahmad et al., 2024; Moon et al., 2009; Oluwole & Cheke, 2009; Pesticide Action Network, 2010). The oxidative imbalance caused by pesticides contributes to various diseases and disrupts natural equilibrium.

While pesticide use has improved agricultural productivity, it has exacted a heavy toll on human health and the environment. Unrestricted application of these chemicals has been linked to numerous health risks, including organ damage, cancer, reproductive issues, and ecological imbalance (Abong'o et al., 2014; Buczyńska & Szadkowska-Stańczyk, 2005; Carvalho, 2017; Schreinemachers & Tipraqsa, 2012). The non-biodegradability of pesticides only intensifies these issues, as they linger in ecosystems and present long-term hazards. As agriculture advances, it is crucial to prioritize environmental conservation and human health protection.

2 Pesticides

Pesticides are a broad category of chemical substances, biological agents, or their mixtures introduced into the environment to prevent, manage, or eliminate populations of harmful insects, weeds, rodents, fungi, and other pests. These substances are essential in modern agriculture and public health, playing a central role in protecting crops and controlling disease vectors. Pesticides achieve pest control through various mechanisms, including attraction and toxic effects, to suppress or eradicate target organisms. Pests, which can include any species threatening food security, health, or human welfare, are countered using a wide range of pesticides, from natural compounds derived from organisms or environmental sources to synthetic chemicals (Mahmood et al., 2015; Sharma et al., 2019).

Pesticides are categorized by type, with common classes including organochlorines, carbamates, organophosphates, pyrethrins, and neonicotinoids, which collectively make up a large portion of currently applied pesticides (Foundation, 2018). These formulations consist of active ingredients along with inert substances, contaminants, and sometimes impurities. Once released, pesticides degrade into metabolites, which can, in some cases, be more toxic than the original compounds

(Carvalho, 2017). Notable for their mobility, persistence, and bioaccumulation potential, pesticides pose significant environmental risks (Fenik et al., 2011). Despite their effectiveness in pest control, the use of herbicides, fungicides, insecticides, acaricides, nematicides, antimicrobials, and rodenticides often comes with drawbacks. Non-selective pesticides may harm non-target species, and the rise of pesticide-resistant pests over time reduces the efficacy of these chemicals (Mahmood et al., 2015).

3 History of Pesticides

Crop cultivation has been a foundational element of human civilization for thousands of years, originating in the Fertile Crescent in Mesopotamia around 10,000 years ago. Throughout history, agriculture has faced continuous challenges from pests and diseases threatening food production. The first known use of pesticides dates back roughly 4500 years to the Sumerians, who used sulfur compounds to control insects and mites (Umetsu & Shirai, 2020). Additionally, the ancient Hindu scripture "Rig Veda," composed around 4000 years ago, mentions poisonous plants employed for pest control (Foundation, 2018).

The evolution of pesticide development can be divided into five phases: pre-1000 CE (early pest management practices), 1000–1850 (use of plant, animal, or mineral derivatives), 1850–1940 (introduction of inorganic products and industrial byproducts), 1940–1970 (adoption of synthetic organic compounds), and post-1970 (development of lower-risk synthetic organics) (Foundation, 2018; Mahmood et al., 2015; Sharma et al., 2019). Following World War II, the advent of organic chemistry significantly advanced pesticide science, marking the start of industrialized pesticide production. Over the last century, numerous pesticide companies have formed in Europe and the United States, with many consolidating in the twenty-first century. This growth in production has fueled global pesticide use, with Japan emerging as a leading producer.

The development of synthetic organic pesticides has focused on three main goals: creating highly effective pesticides that require minimal dosage, designing pesticides that readily degrade to reduce environmental persistence, and developing selective agrochemicals that target specific pests without affecting non-target species (Umetsu & Shirai, 2020). The first goal has resulted in reduced active ingredient quantities necessary for pest control, lessening environmental impact. The second goal has contributed to lower pesticide residue levels in both crops and the environment (Kraus, 1995). The third goal aims to produce compounds that specifically target pests while sparing beneficial organisms, leading to safer, eco-friendly pesticides (Hatfield, 2004).

These strategies have become increasingly important in recent years. For instance, pesticides in the 1930s and 1950s required much higher application rates—ranging from 1 to 10 kg/ha for active ingredients like dinitro-ortho-cresol (DNOC), thiuram, and DDT—resulting in significant environmental impacts. However, advancements in pesticide efficacy now allow for effective pest control at

Table 1 Evolution of pesticides usage

Year	Event
1867	Paris Green (form of copper arsenite) was used to control Colorado potato beetle outbreak
1885	Introduction of a copper mixture by Professor Millardet to control mildew
1892	Potassium dinitro-2-cresylate was produced in Germany
1939	DDT discovered by Swiss chemist Paul Muller; organophosphate insecticides and phenoxyacetic herbicides were discovered
1950s	Fungicides captan and glyodin and insecticide malathion was discovered
1961–1971	Agent Orange was introduced
1972	DDT officially banned
2001	Stockholm Convention

Source: Mahmood et al. (2015)

application rates as low as 10 g/ha (Umetsu & Shirai, 2020; Zadoks & Waibel, 2000). In the past decade, a variety of new pesticides have emerged, including fungicides, insecticides, nematicides, acaricides, herbicides, and biopesticides. Among the 105 chemical pesticides developed or in progress, many are considered safe for human health and environmentally friendly, comprising 43 fungicides, 34 insecticides/acaricides, 6 nematicides, 21 herbicides, and 1 herbicide safener. Although advancements in genomics, structure–activity relationship studies, and chemical biology have propelled pesticide research, only a few breakthroughs have reached widespread application (Joseph Shaba et al., 2019) (Table 1).

4 Production of Pesticides: A Multifaceted Process

The manufacturing of pesticides involves a sequence of carefully orchestrated steps, each essential to producing effective chemical formulations. This process begins with the precise selection of raw materials specific to the type of pesticide being manufactured (Brown, 2006; Llewellyn et al., 2016). These materials undergo synthesis to create the active ingredient, which is crucial for the pesticide's effectiveness. This synthesis stage typically involves intricate chemical reactions that require skilled expertise to achieve the desired compound (Alosaimy et al., 2023; Wang et al., 2015).

After the active ingredient is synthesized, it is formulated into a usable form, commonly as a liquid suspension or emulsifiable concentrate. This formulation step includes combining various inert ingredients such as solvents, emulsifiers, additives, and stabilizers—to enhance the pesticide's stability, effectiveness, and user-friendliness (Abubakar et al., 2020; Carvalho, 2017). Quality control measures are rigorously applied throughout production to ensure that the final product upholds high standards for purity, potency, and safety. These controls involve thorough testing of all materials and products to identify and address potential contaminants or inconsistencies. In the final stage of production, the concentrated pesticide is diluted to an appropriate concentration for its intended use, balancing effective pest control with minimized risks to human health and the environment (Abong'o et al., 2014).

5 Mode of Action of Pesticides

A pesticide's mode of action, or mechanism of action, refers to the specific biochemical interactions through which it disrupts essential biological processes in target organisms. This classification uniquely focuses on the biological pathways that pesticides affect, rather than simply categorizing them by pest type, physical properties, or chemical makeup (Joseph Shaba et al., 2019; Zoccali et al., 2009).

Pesticides can affect target organisms via two main routes: systemic and non-systemic. Systemic pesticides are absorbed by plants or animals and distributed internally, allowing them to impact areas that were not directly treated with the pesticide (Aktar et al., 2009). Conversely, non-systemic or contact pesticides act only when they come into direct contact with the pest, delivering effects at the point of application.

6 Classification of Pesticides

Pesticides can be categorized based on the specific types of pests they are designed to control. Examples include insecticides, fungicides, herbicides, rodenticides, biopesticides, and nematicides (Foundation, 2018) (Fig. 1).

(i) Fungicides are chemical agents designed to prevent and treat fungal infections in crops by targeting and eliminating harmful fungal pathogens. They are primarily classified into two types: inorganic and organic fungicides. Inorganic fungicides include substances like Bordeaux mixture and mercuric chloride, while organic fungicides encompass a wider variety of compounds, such as dithaneS-21, dithaneM-22, and dithaneZ-78 (all carbamates), as well as azoxystrobin, fenpropimorph, iprodione, tebuconazole, thiram, and ziram. Though ziram is effective against fungal pathogens, its toxicity poses considerable risks to aquatic zooplankton, impacting ecosystem health.

(ii) Herbicides and weedicides are chemical agents utilized to control unwanted plants or weeds in agriculture. These substances are classified based on their mode of action and application technique. Selective herbicides are designed to target specific plant species without affecting others, whereas non-selective herbicides eliminate all types of vegetation. Contact herbicides act on plant tissues immediately upon contact, while translocated herbicides are absorbed and spread throughout the plant. Herbicides can be applied to foliage or incorporated into the soil for effective weed control. Notable herbicide classes

Fig. 1 Different types of pesticides

include butachlor, chlorsulfuron, diuron, glyphosate, linuron, metsulfuron methyl, metamitron, triazines (like atrazine and simazine), carbamates (e.g., thiocarbamates, phenyl carbamates), and auxin derivatives (2, 4-D and 2, 4, 5-T). Agent Orange, a notorious herbicide mix of 2, 4-D and 2, 4, 5-T, was used during the Vietnam War. Certain herbicides, such as paraquat, have been associated with an increased risk of Parkinson's disease, and atrazine has demonstrated teratogenic effects, disrupting sex differentiation in frogs during metamorphosis.

(iii) Nematicides are chemical or biological agents used to control or repel nematodes-microscopic, worm-like parasites that damage crops and reduce yields. Chemical nematicides like Aldirab, an acetylcholine esterase inhibitor, are often applied to manage nematode infestations in crops such as tobacco. For example, "Meloidogyne incognita," a common nematode species, attacks tobacco roots, leading to severe yield losses. Biological control agents (BCAs) are also effective; "*Purpureocillium lilacinum*" targets "*M. incognita*" by releasing proteases and chitinase, enzymes that weaken the nematode eggshell to facilitate infection. Another potential BCA, fungi from the genus "*Paecilomyces*," are also promising in nematode control. Other nematicides, such as methyl bromide (MB), ethylene dibromide (EDB), and chloropicrin, are widely used, though their application is sometimes restricted due to environmental concerns. Soil steam sterilization (SSS), which uses heat to inactivate pathogens and nematodes in soil, provides a non-chemical control method by disrupting enzyme function in harmful organisms.

(iv) Rodenticides, commonly known as rat poisons, are substances formulated to control rodent populations. Examples include sodium fluoroacetate, warfarin, red squill, and zinc phosphide. Many of these agents function by disrupting the

Vitamin K cycle in rodents and other mammals, which prevents blood clotting and leads to fatal internal bleeding. Additionally, rodenticides like Vitamin D3, D2, and D1 can cause hypercalcemia (excessively high blood calcium levels) in rodents, leading to severe tissue damage and death. Strychnine, derived from the "Strychnos nux-vomica" tree, is a neurotoxin that causes asphyxiation by inducing muscle spasms. Chloralose, a chlorinated derivative of glucose, is used for controlling rodents and some bird species. Arsenic trioxide combined with copper acetate forms Paris Green, a multipurpose substance used as both a rodenticide and a blue colorant in fireworks.

(v) Insecticides are agents used to control or eliminate insect pests and can be grouped according to their mode of action. Stomach or alimentary canal poisons are ingested by insects, causing toxicity within their digestive systems; examples include azadirachtin from the neem tree (*Azadirachta indica*) and rotenone from the derris plant (*Derris elliptica*). Contact poisons, on the other hand, are lethal upon direct contact with the insect's body, disrupting either the nervous system or the development of the exoskeleton. Pyrethrum, derived from chrysanthemum flowers, and synthetic pyrethroids, which mimic pyrethrum's effects, are well-known contact insecticides.

Fumigants, another type of insecticide, function as gases or vapors that kill insects through inhalation. Commonly used in the treatment of stored grains and enclosed spaces, examples of fumigants include ethylene dibromide (EDB) and methyl bromide.

Insecticides also differ by origin. Natural insecticides, which are extracted from plants or other natural sources, are often seen as environmentally friendlier but may be less potent than synthetic alternatives. Examples of natural insecticides include azadirachtin, rotenone, and pyrethrum. Synthetic insecticides, such as organochlorines, organophosphates, carbamates, pyrethroids, triazines, cypermethrin, insect growth regulators (IGRs), azadirachtin, and hydroprene, are generally more powerful and effective, though they can pose higher risks to human health and the environment due to their persistence and toxicity (Fig. 2).

7 Advantages of Pesticide

Pesticides offer both immediate and long-lasting benefits. Primary benefits, such as the elimination of crop-damaging insects, are directly observable following pesticide application. Secondary benefits, which emerge from these primary effects, persist for extended periods (Mahmood et al., 2015). Pesticide use has garnered significant attention from various stakeholders, including farmers, scientists, governments, and agro-industries (Abubakar et al., 2020).

(i) Pesticides have been hailed as an effective tool in managing agricultural pests, leading to increased crop production. The application of pesticides has

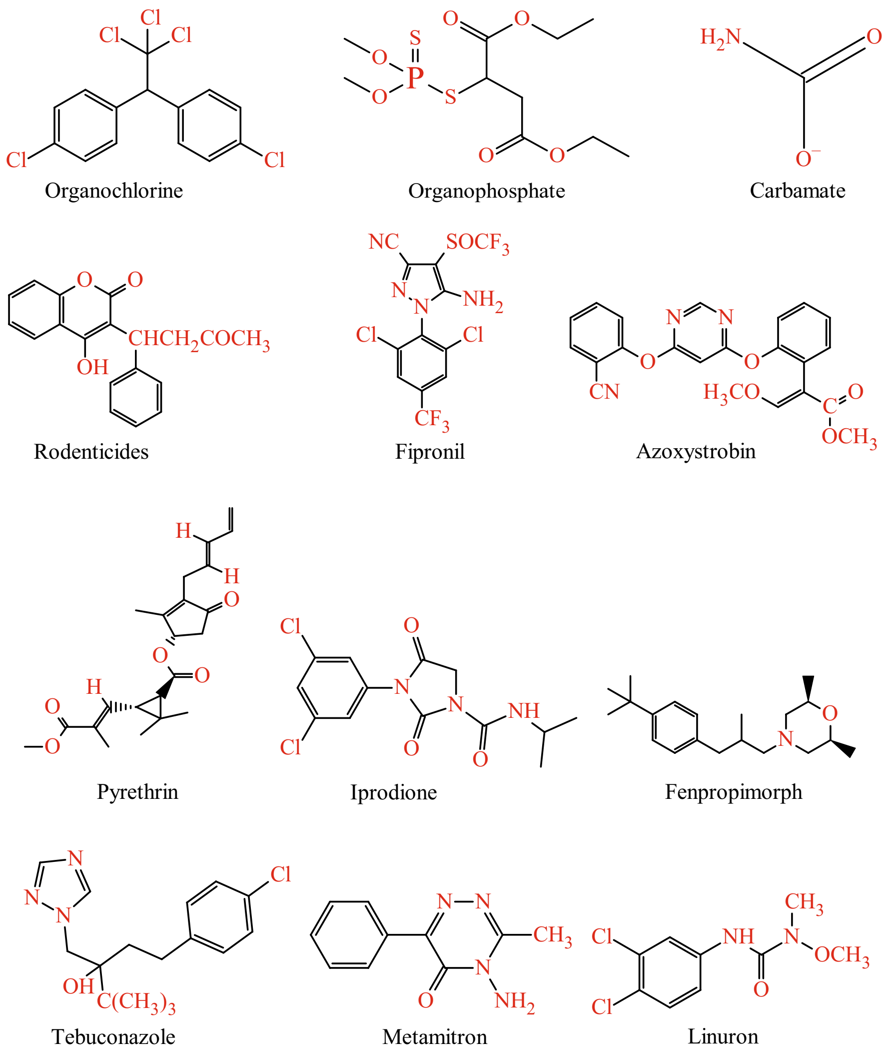


Fig. 2 2D Structure of some common pesticides such as insecticides, fungicides, and herbicide

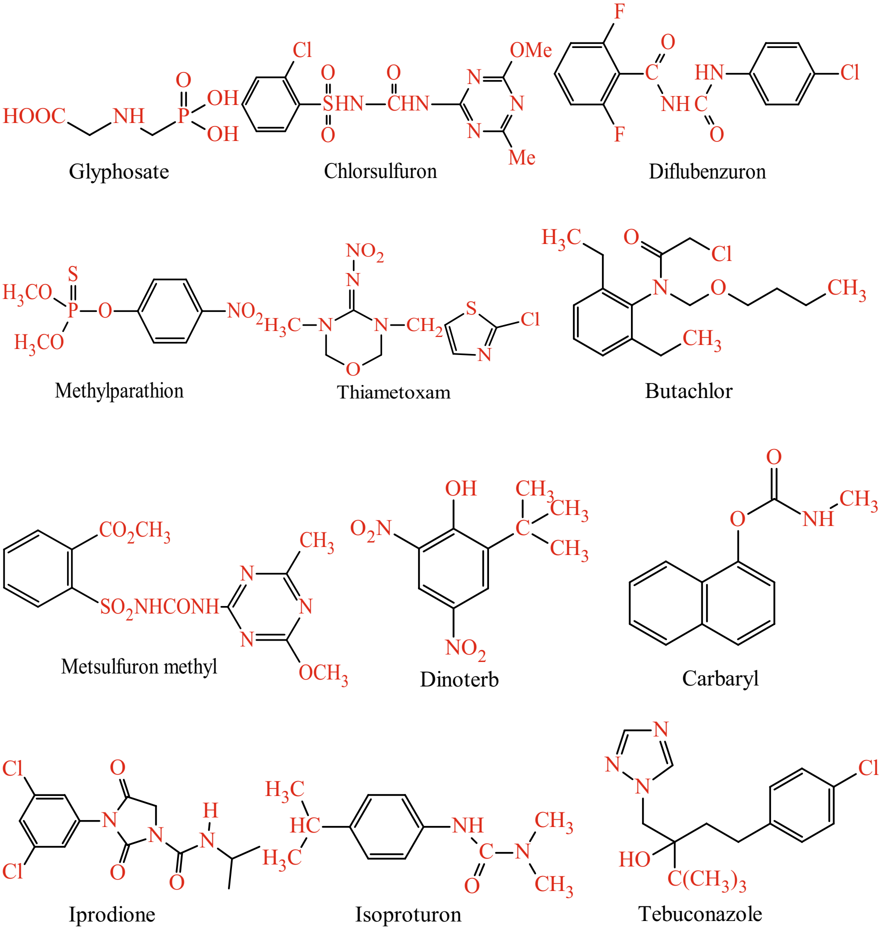


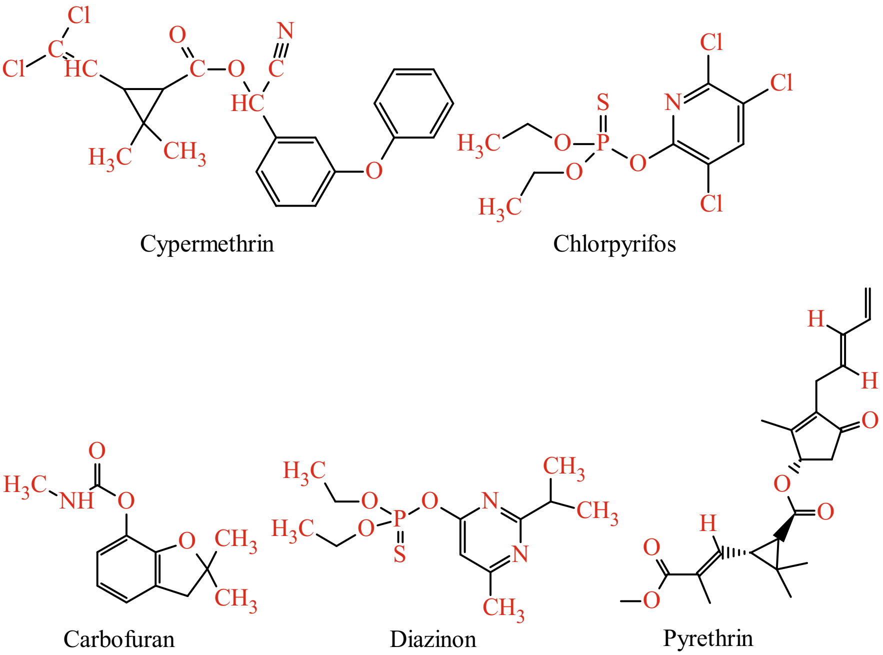
Fig. 2 (continued)

dramatically reduced insect infestations, diseases, and weeds, which can significantly diminish harvestable crop yields and economic returns.

(ii) Pesticide use has contributed to enhanced agricultural production of high-quality food. For instance, the consumption of diets rich in fruits and vegetables outweighs the potential risks associated with consuming low pesticide residues that may remain in some agricultural crops after pesticide application (Pesticide Action Network (Group), 2010).

(iii) Pesticides play a crucial role in preserving wood from destruction by termites and other wood-boring insects. Additionally, they help control the spread of malaria vectors, such as Anopheles mosquitoes (Ross, 2005).

(iv) The adoption of pesticides by farmers for agricultural pest management has motivated scientists and researchers to dedicate significant effort to further



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research and development in the pesticide sector. This has led to the discovery of new types of pesticides with diverse modes of action.

8 Disadvantages of Pesticides

(i) The rampant use of pesticides has led to widespread environmental contamination, posing a significant threat to the quality of soil, water, and air. This contamination can have both short-term and long-term consequences, including the contamination of groundwater and drinking water. The accumulation of pesticide residues in non-target organisms, as observed by Struik and Bonciarelli (1997), further exacerbates the environmental impact (Struik & Bonciarelli, 1997).

(ii) Numerous studies have demonstrated the detrimental effects of pesticides on non-target organisms, including beneficial microorganisms, soil quality, soil enzymes, aquatic microorganisms, and algae (Struik & Bonciarelli, 1997). These unintended consequences disrupt the delicate balance of ecosystems and contribute to environmental degradation.