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An in-depth review of pesticides: Benefits and risks

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A B S T R A C T

This comprehensive review explores the dual facets of pesticides, emphasizing their critical role in enhancing agricultural productivity and disease control while addressing their associated environmental and health risks. It examines the benefits of pesticide use, including increased crop yields, protection against pests and disease vectors, and economic advantages. Conversely, it highlights the potential adverse effects such as environmental contamination, biodiversity loss, resistance development, and human health concerns. The review advocates for sustainable pest management strategies, including integrated pest management and innovative alternatives, to balance the benefits with the pressing need for environmental and public health protection.

Graphical Abstract

1. Introduction

Pesticides have long played a pivotal role in modern agriculture, public health, and pest control. They encompass a wide range of chemical and biological agents designed to eliminate or manage pests that threaten crops, livestock, and human health.[1-6] While their benefits are undeniable, especially in ensuring food security and controlling disease vectors, the associated risks raise critical concerns about environmental safety, human health, and sustainable practices.[7-10] Pesticides are classified based on the target pests and their chemical structures, with main categories including insecticides (such as

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organophosphates, pyrethroids, and neonicotinoids), fungicides (like azoles and chlorothalonil), herbicides (including glyphosate and atrazine), rodenticides (such as warfarin), acaricides (e.g., cyfluthrin), and less commonly, bactericides for bacterial control. Most synthetic pesticides are produced through multi-step chemical syntheses; for example, organophosphates are synthesized by reacting phosphorochloridates with alcohols, pyrethroids are derived from natural pyrethrins via esterification, neonicotinoids involve complex organic reactions forming nitroguanidine structures, and herbicides like glyphosate are manufactured through multi-stage reactions involving amino acids. Biopesticides, such as *Bacillus thuringiensis* (Bt) toxins, are produced via fermentation processes involving microbial cultures under controlled laboratory conditions. On a global scale, pesticide production exceeds 4 million tons annually, with major producers including China, the United States, and Brazil; consumption varies regionally, driven by agricultural practices, pest pressure, and regulations. Developing countries are witnessing increased pesticide use to meet food security needs, contributing to a global market valued at over USD 60 billion. Pesticides exhibit a wide range of physical states, including solids, liquids, and powders, with solubility from highly water-soluble compounds like glyphosate to lipophilic substances such as organochlorines. They vary in stability some degrade rapidly (e.g., carbamates), while others like DDT can persist in the environment. Volatility also differs; for instance, pyrethroids are capable of vaporizing and dispersing through the air. Environmental behavior is further influenced by parameters such as pH and partition coefficients, which affect their absorption, bioaccumulation, and mobility in ecosystems. This review aims to provide an in-depth analysis of both the positive contributions and the potential hazards associated with pesticides, highlighting the importance of responsible use and ongoing innovation in pest management strategies. Understanding the complex interplay between these factors is vital for shaping policies and practices that support sustainable development, food security, and public health in a changing world.

2. Benefits of pesticides

2.1. Enhanced agricultural productivity

Pesticides have revolutionized agriculture by enabling farmers to significantly increase crop yields and improve crop quality.[11-12] Before their widespread adoption, pest infestations caused devastating losses in crops, often leading to food shortages and economic hardship. The application of pesticides effectively controls insects, fungi, weeds, and other pests that threaten plants, thereby reducing crop damage during critical growth periods.[13-17] This control allows farmers to cultivate crops more intensively and over longer periods, boosting overall productivity. Pesticides also enable the cultivation of higher-value crops that might be too vulnerable to pests and diseases without chemical protection. For example, fruit and vegetable crops are particularly susceptible to pests, and pesticides help ensure consistent supply and quality.[18-20] Furthermore, pesticides contribute to minimizing crop failures in vulnerable regions, especially in tropical and subtropical areas where pest pressure is high. They also extend growing seasons by protecting crops from seasonal pest outbreaks, thereby contributing to food security. With effective pest control, farmers can reduce crop losses during harvesting and storage, ensuring a more stable supply of food products.[20-21] Technological innovations have enhanced pesticide formulations, making them more targeted, efficient, and environmentally friendly. The integration of pesticides with modern farming practices like precision agriculture allows for optimized application, reducing waste and environmental impact.[22-23] Overall, pesticides have been instrumental in supporting the Green Revolution and feeding the world's increasing population. Their role in maintaining high productivity levels is vital for economic development and social stability in many regions.

2.2. Disease control

Pesticides play a crucial role in controlling disease vectors, significantly reducing the burden of infectious diseases worldwide. Malaria, dengue fever, Zika virus, chikungunya, and other vector-borne illnesses are transmitted by mosquitoes, ticks, and flies, which thrive in environments where pests are abundant. The strategic use of insecticides and larvicides in vector control programs has been instrumental in decreasing disease transmission rates, saving millions of lives annually. For instance, indoor residual spraying with insecticides has been a cornerstone of Malaria control, especially in endemic regions. Similarly, fogging and larviciding are used to combat mosquito populations during outbreaks.[24-27] Beyond vector control, pesticides also help prevent the spread of plant and animal diseases caused by fungi, bacteria, and viruses. Fungicides, for example, protect crops from devastating fungal infections that can wipe out entire harvests, thereby safeguarding food security and farmers' incomes. In livestock management, pesticides and acaricides control parasitic pests that weaken animals and transmit diseases.[28-30] These measures collectively contribute to public health by reducing the incidence of vector-borne illnesses, which disproportionately affect impoverished and rural populations. The development of targeted pesticides and integrated disease management strategies has further enhanced their effectiveness. Nonetheless, reliance on pesticides must be balanced with environmental and health considerations, as improper use can lead to resistance and ecological harm. Overall, pesticides remain vital tools in the ongoing fight against infectious diseases and food safety threats.

2.3. Economic advantages

The economic benefits of pesticides extend across multiple sectors, including agriculture, food processing, storage, and export markets. By protecting crops from pests, pesticides help farmers achieve higher yields and superior quality, directly increasing their income and economic stability. This productivity boost reduces the risk of crop failure, which is particularly crucial during droughts, floods, or pest outbreaks. The increased agricultural output supports local economies, sustains rural livelihoods, and contributes to national gross domestic product.[24,31-32] Moreover, pesticides reduce the costs associated with crop loss, manual pest control labor, and post-harvest spoilage. They enable farmers to cultivate a wider variety of crops, including high-value specialty crops, which can fetch premium prices in local and international markets. The availability of affordable and effective pesticides has facilitated global trade by ensuring compliance with quality standards, reducing rejection of exported goods due to pest contamination. The agricultural sector's resilience and productivity, driven by pesticide use, underpin food security and economic growth in many developing countries. Additionally, pesticide-related innovations stimulate research, manufacturing, and distribution industries, creating jobs and fostering technological advancements. While reliance on pesticides raises concerns about sustainability, their economic contribution remains significant, especially in regions where agriculture forms the backbone of the economy.

2.4. Protection of stored products

Post-harvest pest management is critical for maintaining the quality, safety, and longevity of stored agricultural products.[33-34] Pests such as insects, rodents, and fungi can cause massive losses during storage, leading to economic hardship for farmers and traders. Pesticides, including fumigants and insecticides, are widely employed to protect stored grains, nuts, dried fruits, and other commodities. Proper application of these chemicals prevents infestations that can spoil food, reduce nutritional value, and generate mold or mycotoxins that pose health risks.[35-36] Effective pest control during storage extends the shelf life of products, reduces food waste, and stabilizes supply chains, especially in regions with limited cold storage or transportation infrastructure. It also helps prevent the spread of pests to new areas through trade and shipment, maintaining compliance with international standards. The use of pesticides in storage facilities supports economic stability by safeguarding farmers' investments and ensuring that food reaches markets in good condition.[37-38] Moreover, pesticides used in post-harvest applications are often applied in controlled environments, minimizing environmental impact and residue concerns when managed correctly. This protection is critical for global food security, reducing losses and ensuring that nutritious food remains accessible and affordable.

3. Risks and concerns associated with pesticides

3.1. Environmental impact

Despite their benefits, pesticides pose significant threats to the environment. Many pesticides are toxic to non-target species, including vital pollinators such as bees, butterflies, and other beneficial insects that are essential for pollination and biodiversity.[39-41] Their runoff can contaminate water bodies, leading to pollution of lakes, rivers, and groundwater, which adversely affects aquatic life and ecosystems.[42-43] Persistent pesticides, which degrade slowly, tend to accumulate in the soil and sediments, causing long-term contamination and bioaccumulation in plants and animals. Such accumulation can disrupt food chains and ecological balance.[44-46] Pesticide drift during spraying can impact neighboring ecosystems, killing or harming non-target flora and fauna. The decline in pollinator populations due to pesticide exposure has serious implications for crop pollination, biodiversity, and ecosystem resilience. Additionally, soil health can be compromised, affecting microbial diversity crucial for soil fertility. The environmental footprint of pesticides underscores the importance of developing safer, biodegradable, and targeted pest control agents to reduce ecological harm.[47-50]

3.2. Human health risks

Human exposure to pesticides occurs through multiple pathways, including inhalation during spraying, skin contact, and ingestion of residues present on food and water.[51-52] Chronic exposure to certain pesticides has been linked to serious health issues such as cancers, neurological disorders, reproductive problems, and endocrine disruption.[53-54] Agricultural workers and pesticide applicators face higher risks due to frequent and direct contact, often compounded by inadequate personal protective equipment and training. Consumers may be exposed to pesticide residues on fruits, vegetables, grains, and processed foods, raising concerns about cumulative health effects.[55-56] Residue levels are regulated, but violations and illegal use still occur, and long-term exposure to low doses of multiple pesticides may pose additive or synergistic health risks. Vulnerable groups like children, pregnant women, and immunocompromised individuals are particularly susceptible. Studies have documented instances of acute poisoning and chronic illnesses linked to pesticide exposure, emphasizing the need for strict regulation, safe handling practices, and development of less toxic alternatives. Protecting human health requires balancing pest control needs with rigorous safety standards.[57-59]

3.3. Development of resistance

Pests can develop resistance to pesticides through genetic adaptation, rendering certain chemicals ineffective over time. Resistance arises when pests are repeatedly exposed to the same class of pesticides, selecting for resistant individuals. This

phenomenon complicates pest management, leading to increased application rates, higher costs, and the use of more toxic chemicals. Resistance can also cause pest outbreaks, as control measures lose their efficacy, resulting in economic losses and increased environmental contamination.[60-62] The overreliance on chemical control without integrated approaches accelerates resistance development. Managing resistance requires strategies like rotating pesticides with different modes of action, integrating biological controls, and adopting cultural practices. Failure to address resistance undermines pest management programs and threatens crop yields, food security, and ecological health.

3.4. Residue concerns

Pesticide residues in food products present ongoing health and trade challenges. Residues are traces of chemicals remaining on or in food after application, which can accumulate over time.[63-64] Although regulatory agencies establish maximum residue limits to ensure safety, concerns persist about the long-term effects of consuming small amounts of multiple residues, especially when combined. Residues can enter the food chain through soil, water, or direct application, and may persist or bioaccumulate in certain environments.[65-69] Improper application, inadequate washing, or processing can increase residue levels on food. Residue concerns impact consumer confidence, especially with increasing demand for organic and chemical-free foods. International trade restrictions and rejections also occur due to non-compliance with residue standards. Therefore, proper pesticide management, adherence to pre-harvest intervals, and development of safer alternatives are essential to mitigate residue-related risks.[70-74]

4. Balancing benefits and risks

Achieving a sustainable balance between the benefits and risks of pesticides requires a multifaceted approach. Policymakers must implement strict regulations, enforce compliance, and promote research into safer, environmentally friendly alternatives. Promoting integrated pest management strategies that combine biological controls, crop rotation, resistant varieties, and judicious pesticide use can reduce reliance on chemicals. Educating farmers and applicators on proper handling, application rates, and protective measures minimizes health and environmental risks.[75-76] Investment in the development of biodegradable, targeted, and less toxic pesticides is essential for sustainability. Consumer awareness campaigns can promote safe food handling and support organic and sustainable products. International cooperation and harmonization of standards are needed to address residue and trade issues. Ethical considerations should guide policies to protect vulnerable populations and future generations. Emphasizing ecological balance and biodiversity conservation alongside crop protection ensures long-term sustainability. Ultimately, sustainable pest management practices aim to maximize societal benefits (food security, economic stability, and health) while minimizing environmental and health hazards. This integrated approach fosters resilience in agriculture and public health systems, ensuring that pesticide use remains beneficial rather than detrimental.[75-80]

5. Conclusion

Pesticides remain a vital tool in modern agriculture and public health. However, their use must be carefully managed to mitigate environmental and health risks. Ongoing research, stricter regulations, and the adoption of sustainable practices are essential to maximize benefits and protect ecosystems and human well-being for future generations.

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