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Pesticides in modern agriculture: Assessing health effects, risk perception and policy implications for safer food systems

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Abstract

Pesticides have long been necessary to modern agriculture and food systems, enabling the achievement of high crop yields and ensuring food security. However, their widespread use raises concerns about the health effects of pesticide residues in food, especially for vulnerable groups like children and pregnant women. This review examines the dual role of pesticides in boosting agricultural productivity and their potential health risks. It discusses the benefits of pesticide use, including increased crop yields and public health benefits, while critically analyzing evidence that links long-term exposure to pesticide residues with health issues such as cancer, reproductive problems, neurotoxicity, and genetic damage. A specific focus is given to the increased vulnerability of developing fetuses and children because of their physiological and developmental sensitivity. The article also examines consumer perceptions of risk, highlighting gaps in public understanding and the impact of misinformation on food choices. Finally, this article reviews international and national regulations, including the roles of the U.S. Environmental Protection Agency and the Codex Alimentarius, in regulations aimed at protecting public health. Despite progress, challenges remain in harmonizing regulations, enforcing compliance, and effectively communicating risks. The review suggests strategies to close knowledge gaps through targeted education, transparent labeling, and better monitoring systems. It promotes integrated approaches that combine strong regulatory oversight, public engagement, and industry innovations like Integrated Pest Management to reduce dependence on pesticides. These efforts are crucial for aligning consumer perceptions with scientific evidence, thereby ensuring safe, sustainable, and equitable access to food worldwide.

Keywords: Pesticide; Food; Food Safety; Consumer Risk Perception; Food Labeling; Risk Communication; Pesticide Regulation

1. Introduction

1.1. Overview of Pesticides in Modern Agriculture

Pesticides have revolutionized modern agriculture, allowing farmers to control pests, increase crop yields, and maintain stable food supplies in the face of increasing global demand [1,2]. The use of pesticides has become deeply entrenched in agricultural practices, with millions of pounds applied annually across crops ranging from fruits and vegetables to grains and nuts. According to a 2009 study, it was estimated that over a billion pounds of pesticides are used in the United States each year, with 5.6 billion pounds used worldwide. [3]. The U.S. Environmental Protection Agency (EPA) is the federal agency responsible for regulating how these chemicals are used in a way that they do not pose "unreasonable risks" to human health or the environment. However, traces of pesticide residues often remain on harvested produce, drawing concerns among consumers about potential health risks from chronic exposure to these foods [4-6].

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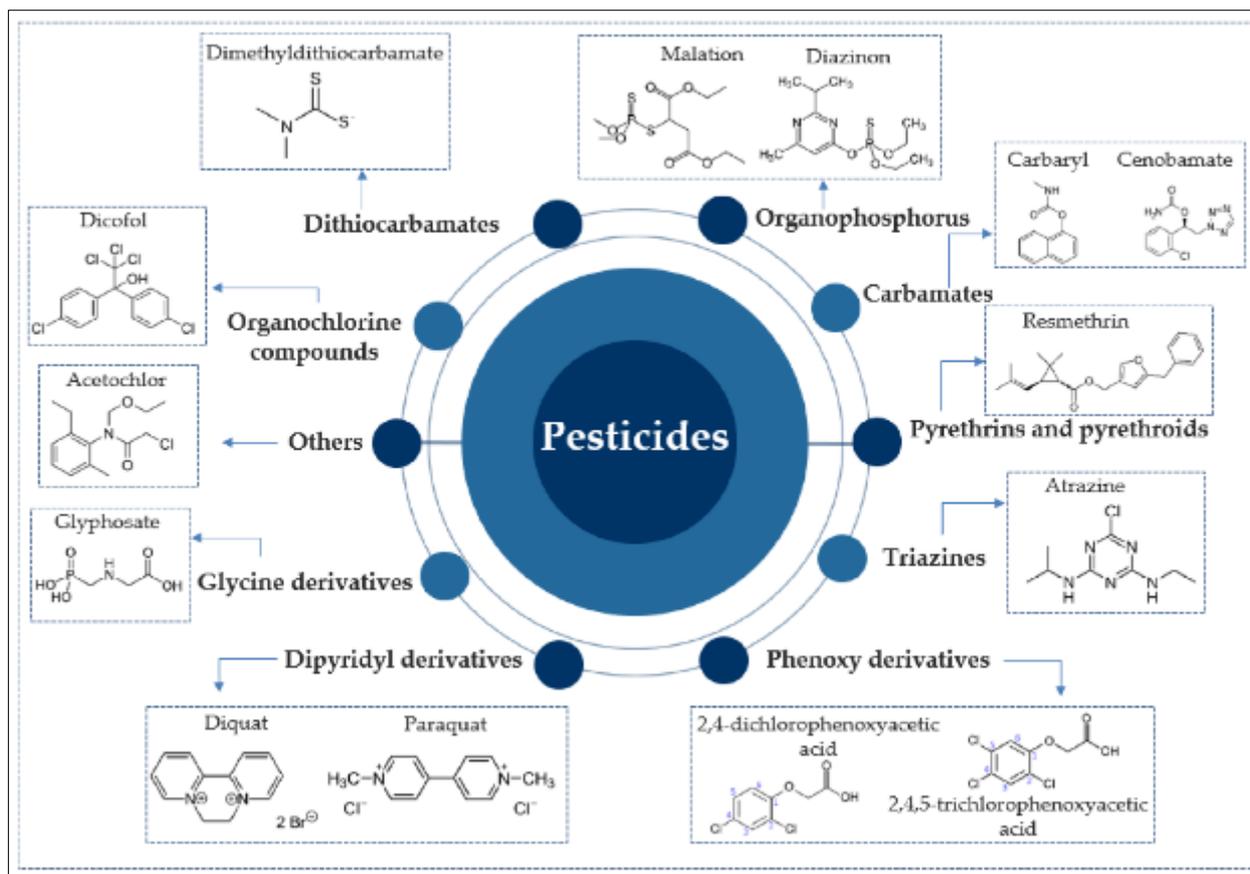


Figure 1 Types of Pesticides [7]

1.2. Purpose and Scope of the Article

This review synthesizes existing knowledge on consumer interest and risk perception related to pesticide use. It revisits the role and merits of pesticides in agriculture while critically examining their health effects, with particular attention to the heightened vulnerability of children and pregnant women. The review briefly addresses consumer risk perception and explores regulatory frameworks governing pesticide use at international, national, and U.S. levels. By analyzing empirical studies and policy structures, it highlights key challenges in public awareness and communication, offering recommendations to enhance transparency, strengthen risk assessments, and promote safer pesticide practices. In light of all this information, the article advocates for an integrated approach that combines explicit policy action with robust consumer education to align public perceptions with scientific evidence and ensure safe and equitable access to food.

2. Pesticide Use and Benefits

Pesticides are various chemical compounds, including fungicides, insecticides, herbicides, nematocides, rodenticides, plant regulators, and others. They have made significant contributions to controlling harmful organisms and enhancing agricultural productivity. Ideally, pesticide use would target and kill pests while remaining harmless to unintended targets, such as humans; however, that is not always the case. Some pesticides, especially those known as organochlorines, have been banned due to their persistence in the environment and the difficulty in breaking them down.

The use of pesticides has numerous benefits, spanning public health, agriculture, and biodiversity. Over the years, food production has increased as a result of the use of pesticides. Research has shown that in India, for example, food grain production was around 50 million tons in 1948-1949 and it increased to about four times to 198 million tons by the end of 1996-1997, from an estimated 169 million hectares of permanently cropped land [8]. The same dramatic increases have been seen in wheat yields in the United Kingdom [9] as well as corn yields in the USA [10]. Without pesticides, there would have been considerable economic losses from weeds, disease, and insect pests, which significantly affect the amount of food produced that can be harvested.

In 2022, total pesticide use in agriculture was 3.70 million tonnes (Mt) of active ingredients, marking a 4 percent increase with respect to 2021, a 13 percent increase in a decade, and a doubling since 1990. Between 1990 and 2022, pesticide intensities increased at varying rates: use per cropland area increased by 94%, use per value of agricultural production by 5%, and use per person by 35%. In the Americas, pesticide use in agriculture increased by 10 percent from 2021 to 2022 [11].

2.1. Health Effects of Pesticide Residues in Food

2.1.1. Introduction to Health Effects of Pesticides

Pesticides have become important to modern agriculture, especially in ensuring global food security by controlling pests, diseases, and weeds. Due to their extensive use, residues have persisted in food products, raising significant concerns about their potential impact on human health. While some pesticide residues found in food are within the limits established by national and international regulatory agencies, there is growing scientific evidence that suggests that even low-level, chronic exposures may have long-term health consequences, especially when considering the cumulative effects of multiple pesticides consumed together, commonly referred to as the “cocktail effect.” [12,13]

Vulnerable populations, including children, pregnant women, and individuals with pre-existing health conditions, are of particular concern due to their heightened physiological sensitivity and developmental stages. Studies increasingly indicate that dietary exposure, which was once considered negligible compared to occupational exposure, may contribute meaningfully to chronic disease risks, necessitating a more precautionary approach to risk assessment [14]. This section briefly reviews the human health effects that pesticide residues on food may cause and underscores the differential risks faced by sensitive population groups.

2.2. Health Effects of Pesticide Residues

Pesticide residue can enter humans directly through food ingestion or indirectly through skin contact. Upon intake, pesticides move through the blood all over the body until they are expelled through urine, the skin, and exhaled air [15]. The time and exposure of concentration are factors that influence how severe the effects of pesticides can be in the human body [16]. The concentration of pesticides in food is a result of growing food in water and soil that is contaminated with pesticides. The quaternary nitrogen compounds, such as paraquats of pesticides, are associated with neurodegenerative diseases such as Parkinson's Disease [17]. Also, pesticides are known to cause cancer, necrosis, asthma, reproductive disorders, diabetes, and cardiac diseases among many others [18]. A group of pesticides known as carbamates inhibits the acetylcholinesterase activity and is used as a biomarker of neurotoxicity [19]. Cancer is a significant disease that can be caused by pesticide residue in food. Breast cancer is the most common cancer that is associated with organophosphates, and the mechanism of action is through affecting cellular growth as well as proliferation [20]. Human fertility can be affected by pesticides in food. In addition, genital tract anomalies are formed. This is achieved through endocrine hormones that regulate the timing of hormone release. Not only by affecting when hormones are released, but pesticides can also imitate hormones themselves, resulting in these issues [20]. People can also develop coronary artery disease as a result of the reduction in paraoxonase activity of organophosphates [21]. The DNA of humans can also be affected by pesticide residues. The damage pesticides do to the human gene is very catastrophic with some studies noting that it is much greater than smoking and alcohol consumption [22]. Sperm DNA damage and reduction in human semen quality are also effects of pesticides [23]. Other genetic deleterious effects of pesticide residues in humans include genetic methylation [24], oxidative stress [25], breaks in the DNA strand, and oxidative damage [26].

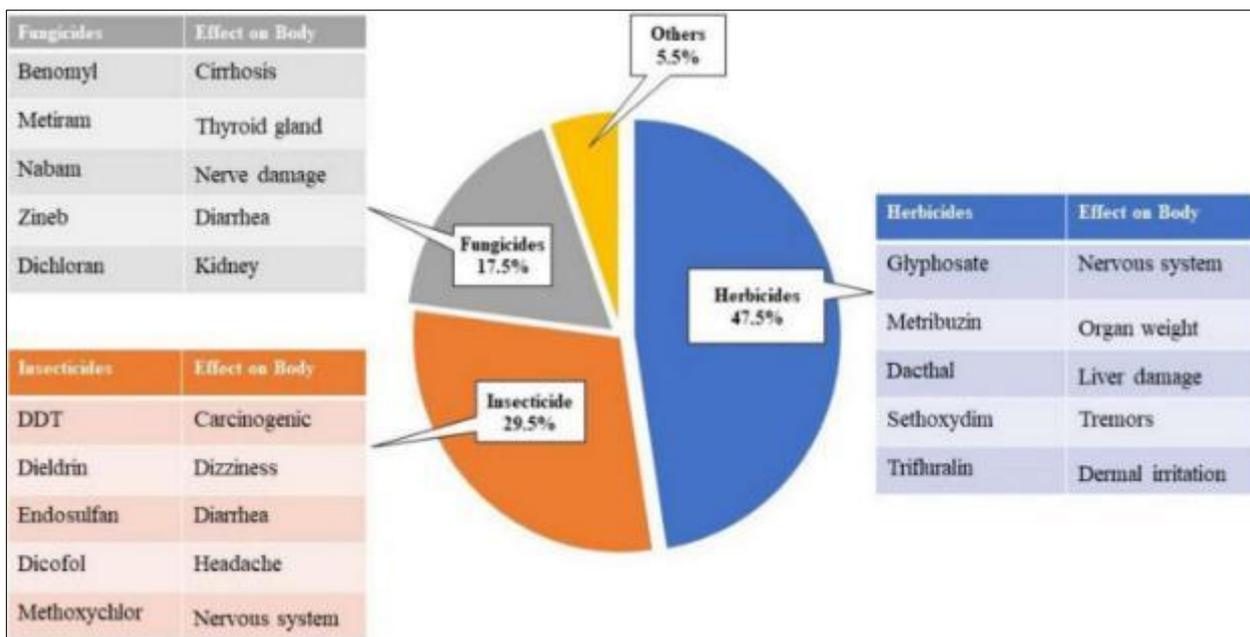


Figure 2 Health Effects of Pesticides [27,28]

2.3. Vulnerability in Children and Pregnant Women

Children and pregnant women are two of the most vulnerable groups to pesticide exposure because of their unique physiological and developmental characteristics. For a long time, pesticides have been studied for their ability to cross the placenta [29]. The fetus and young child undergo rapid cellular growth and differentiation, during which even the most minute disruptions in hormonal signaling or neurodevelopment can result in long-term health consequences [30]. Moreover, children’s metabolic systems are immature, and their detoxification pathways are less efficient than those of adults, which increases their susceptibility to toxins in pesticide residues [31].

Studies have consistently shown that prenatal exposure to pesticides is associated with adverse birth outcomes [32–34]. Research has shown that pesticides can alter physiological and molecular levels, which may cause adverse pregnancy outcomes [35]. For example, research in the United States and Europe has linked maternal pesticide exposure to increased risks of preterm births, low birth weight, and congenital anomalies [36,37]. Additionally, research has shown a positive association between environmental or occupational exposure to some pesticides and some congenital anomalies [37].

The heightened vulnerability of these groups underscores the urgent need for protective measures in both regulatory frameworks and public health interventions. Safeguards that consider cumulative exposure and critical windows of development are essential to prevent lifelong consequences from early-life pesticide exposure.

3. Consumer risk perception

Public interest and concern in pesticide residues on food have greatly increased in recent years in the media. In Germany, for example, organic and conventional consumers report a high level of concern about findings of pesticide residues in food. This observation is consistent with how consumers show concern about pesticide use in other countries [38]. It is worth noting that organic consumers take a more critical stance to pesticides compare to conventional consumers [38]. In Uganda, consumers are aware of pesticides residue on their fruits and vegetable [39]. Knowing this, they agree that long-term exposure to these chemicals puts them at risk of developing illnesses such as cancer, kidney, and liver disease, among others. They rely on mitigation measures such as drying, peeling, washing, and cooking to remove these pesticides from food items. Additional studies from Ghana[40], as well as five different countries (Poland, Ireland, the Netherlands, France and Brazil) corroborate the fact that consumers are very concerned about pesticides residue on food [41]. Farmers’ knowledge of pesticides and their safe use in terms of amount and time has made consumers uncomfortable with the taste of fruits and vegetables. For example, a study on fruits and vegetables showed that females are more aware of pesticides in this food and this may be because they have more free time to study about health and safety products that they buy [42]. People with a higher level of education are also more likely to be aware as research respondents [42] showed a significant and positive effects.

With rising consumer concern, there are gaps in knowledge as well as a lot of misconceptions [43]. Many consumers mistakenly believe that organic foods are of higher quality and may be free of pesticides or that any detectable residue, regardless of its level, represents a significant health hazard [44,45]. At the same time, scientific communication about risk assessment including pesticide risks is complex because these concepts are nuanced [13], including acceptable daily intake (ADI), cumulative exposure, and differences in pesticide toxicity [46]. Additionally, there is a lack of adequate information in the literature regarding the direct labeling of substances in relation to pesticide risk. These complications may leave consumers relying heavily on organic certification or third-party guides as a proxy for demonstrating the safety of produce.

3.1. Overview of Pesticide Regulatory Context

3.1.1. International Regulatory Framework

Around the world, pesticide regulation involves national agencies and international bodies such as Codex Alimentarius, which is established by the FAO and WHO [47]. These agencies evaluate and approve pesticides, setting limits on the amount of residue that can legally remain on food through maximum residue limits (MRLs). These limits are based on toxicological data, exposure assessments, and built-in safety factors to protect vulnerable populations. In the United States, the Environmental Protection Agency (EPA), the U.S. Department of Agriculture (USDA), and the Food and Drug Administration (FDA) are the governmental agencies responsible for regulating the use of pesticides.

The Food and Agriculture Organization (FAO) adopted the International Code of Conduct on the Distribution and Use of Pesticides in 1985. From there, they added it to the Prior Informed Consent (PIC) procedure in 1989 and revised it in 2002. The code was expanded to cover public health pesticides and was renamed to the International Code of Conduct on Pesticide Management. The World Health Organization (WHO) adopted this into its framework for its guidance in 2014 [48]. The Codex Alimentarius Commission (CAC), established by both the FAO and WHO, sets internationally standardized food standards, which the World Trade Organization (WTO) recognizes through its Agreement on the Application of Sanitary and Phytosanitary Measures. The Codex Committee on Pesticide Residues (CCPR), a subsidiary of the CAC, is responsible for developing MRLs. The CCPR sets MRLs for pesticides in foods and animal feeds, determines testing methods for MRLs, and creates a priority list of pesticides for assessment by the Joint FAO/WHO Meeting on Pesticide Residues [49]. MRLs are set well below levels that are considered harmful to consumers. Typically, they are established with a significant safety margin, often 100 times lower than the No Observable Adverse Effect Level (NOAEL), the highest exposure level at which there are no observable adverse effects in toxicological studies. This margin accounts for uncertainties that may arise, as well as differences among people, thereby ensuring the public's safety [50]. MRLs can still be significantly different across countries despite the standardization. In Europe, the European Food Safety Authority (EFSA) is responsible for recommending MRLs of pesticides allowed in foods and feeds sold within the EU. Before establishing or modifying an MRL, EFSA conducts comprehensive risk assessments of pesticides to ensure food safety [51]. The issue is that the current EU policy does not fully address the challenges posed by legacy pesticides or the need for their remediation [52].

3.1.2. National Regulatory Frameworks

The National Regulatory Frameworks differ from country to country due to variations in laws, institutional capabilities, and government resources and plans. The national regulations are a reflection of a country's economic and social condition, including the pest issues, plant diseases, and the environmental climate [52].

As international figureheads, the FAO and WHO have provided a framework that supports countries in developing or improving their regulations and structures. This is through providing information and supporting programs to align with their various standards, such as Codex Alimentarius. Governments adopt these standards, such as the maximum residual limits, so that they comply with international standards [52]. This is especially true for goods that are traded, but they can be flexible when it comes to their national limits [53].

At first, governments did not have adequate pesticide regulations as a result of gaps in knowledge, but there has been some progress, as well as knowledge gaps, especially regarding pesticides that are poisonous to human health, as well as how pesticide residues are able to remain on food. Now, there is abundant research that fills this gap and examines their health effects [4,21,29]. Despite the progress that has been made, the laws that nations make do not hold up well against the established standards. National laws do not fully align with internationally set standards, and there are no structures to enforce the regulations that have been set. This is commonly seen in settings when resources are limited because of inadequate operational structures to uphold the set laws [54]. There are also differences in terms of pesticide regulations [55] These differences result in trade barriers because the MRLs can differ by country. Also, some pesticides may be approved for use in a particular country, but they may not be legal to use in another. The ideal situation is that

nations consider and adopt the standards set by the FAO and the WHO. Countries have many approaches to choose from. One is that some may adopt treaties and draft tailored laws and regulations that reflect the core objectives of international agreements while adapting them to their local socio-economic, environmental, and governance contexts. Another approach may be partial adoption, where countries may selectively adopt some provisions of international regulations because of the economic, ecological, and legislative limitations they may face. Over time, they could gradually adopt all the provisions provided by international agencies. This may be particularly relevant for low-income countries and settings, allowing nations to demonstrate good faith in adhering to international standards while also being flexible in accordance with their specific circumstances. These varying approaches allow states to reconcile global expectations with national priorities and capacities, ensuring that pesticide governance remains both practical and contextually appropriate.

3.1.3. Regulatory Frameworks in the United States of America

In the United States, pesticide regulation is primarily the responsibility of three federal agencies: the Environmental Protection Agency (EPA), the U.S. Department of Agriculture (USDA), and the Food and Drug Administration (FDA). Each of these agencies plays a special role in ensuring the safety of pesticide use in food production.

The EPA evaluates and approves pesticides for use, setting limits on the amount of residue that can legally remain on food through established tolerance levels known as Maximum Residue Limits (MRLs). These tolerance levels are based on toxicological data, including animal studies and exposure assessments, with built-in safety factors to protect vulnerable populations such as children and pregnant women. [56]. Once a pesticide is approved, the USDA and FDA are responsible for monitoring residue levels in food to ensure compliance with the standards that the EPA has set regarding the tolerance levels.

The USDA conducts the Pesticide Data Program (PDP), an annual surveillance effort testing thousands of food samples for pesticide residues. The PDP reports consistently show that over 99% of tested foods comply with legal limits, and many contain residues far below established tolerances [57]. However, these reports may go unnoticed by the public, as they are published in technical formats that are more accessible to scientists and policymakers than they are to the average consumer.

4. Recommendations for Improvement

4.1. Policy-Level Consumer Recommendations

To address consumer concerns and close knowledge gaps about pesticides and their residues in food, policymakers should consider adopting standardized, science-based methods for pesticide disclosure. One potential strategy is the introduction of voluntary residue labels, which would encourage producers to clearly indicate when pesticide residues are present at levels below regulatory thresholds. Research [58] has shown that a transition towards more informative and visually intuitive labels, such as traffic lights or image-based systems, could empower consumers to make more discerning decisions and minimize exposure to potentially hazardous chemicals in pesticides. This approach could enable consumers who are especially sensitive to residue concerns while allowing producers to demonstrate their commitment to transparency. In implementing labeling changes, it is important for policymakers to work with pesticide manufacturers to foster compliance and facilitate the smooth adoption of effective label designs that align with both public health objectives and industry standards.

Another promising option may be the use of QR codes on food packaging to provide digital access to detailed residue test results. This technology would enable interested consumers to easily retrieve current information about the safety of their food. The research results of Rotsios et al. [59] show that a QR Code on the packaging of food products, which directs consumers to entertaining and enriched content, results in an increased level of usage intention. Moreover, they demonstrated that comprehension and self-confidence increase with the adoption of the QR Code.

Furthermore, policymakers could improve public understanding by reforming the USDA Pesticide Data Program (PDP) into accessible annual summaries that use infographics and plain language explanations. Such tools would make technical data more understandable and promote informed decision-making among a broader audience.

In addition to improving disclosure mechanisms, strengthening regulatory oversight of pesticide use remains critical for maintaining public trust in food safety systems. Policymakers should consider routinely reviewing and updating maximum residue limits (MRLs) to reflect the latest scientific evidence on pesticide safety and environmental impact. Enhanced monitoring programs and stricter enforcement of existing regulations could further reassure consumers that

food safety authorities are vigilant in protecting public health. Together, these initiatives would address both the informational needs and safety expectations of consumers, promoting confidence in the food supply while supporting evidence-based policymaking in agricultural practices.

4.2. Public Education and Outreach

Strong public education efforts are crucial for closing the gap between consumer perceptions and scientific facts about pesticide use and food safety. Many consumers do not fully understand how pesticides are applied in farming, how residue levels are regulated, and the extensive safeguards in place to protect human health and the environment [6,39–41]. This lack of knowledge can cause anxiety, skepticism, and mistrust of the food system. To address these issues, national food safety campaigns could be launched, inspired by successful public health initiatives such as anti-smoking campaigns or nutrition labeling programs. These campaigns would aim to communicate complex scientific information in clear, relatable language. By explaining how pesticides help maintain crop yields and food security, detailing how residue levels are monitored and kept within strict regulatory limits, and highlighting oversight by agencies such as the USDA and EPA, these efforts can help consumers make informed and confident choices. Utilizing multiple platforms—such as television, social media, radio, and community events—would allow outreach to a broad and diverse audience, ensuring messages resonate across various demographic groups.

In addition to national outreach efforts, embedding food safety education within school systems can create long-term change by fostering scientific literacy from an early age [13]. By incorporating topics like pesticide use, food systems, and environmental health into science curricula, educators can help students develop critical thinking skills and a nuanced understanding of these issues before they become adult consumers. Classroom activities, interactive learning tools, and field trips to farms or food safety laboratories could bring these concepts to life and cultivate curiosity rather than fear about how food is grown and regulated. Over time, this approach would nurture a generation of well-informed individuals who are better equipped to engage constructively with food safety policies and make decisions grounded in evidence. Beyond schools, youth programs and extracurricular initiatives, such as 4-H clubs or community garden projects, could further reinforce these lessons in practical, hands-on ways. Furthermore, strategic partnerships with trusted organizations can amplify the reach and impact of public education efforts, particularly in communities where misinformation or cultural barriers may hinder understanding. Collaborating with community-based organizations, healthcare providers, agricultural extension services, and faith-based groups allows messaging to be tailored to local contexts and delivered by individuals who already hold the trust of their communities. These partnerships could produce culturally relevant materials, such as translated resources, workshops, or informational sessions designed for specific audiences. Mobile health units, farmers' markets, and local events could also serve as venues for outreach, helping to ensure that accurate information reaches even underserved or hard-to-reach populations. Together, these multi-faceted strategies, such as national campaigns, school-based programs, and grassroots partnerships, can create a more informed public, reduce unnecessary fear around pesticide residues, and strengthen overall confidence in the food supply system.

4.3. Encouraging Industry Innovation

The food industry plays a pivotal role in shaping agricultural practices, and it should be incentivized to adopt Integrated Pest Management (IPM) and other sustainable strategies that minimize pesticide use without compromising crop yield or quality [60]. IPM emphasizes a holistic approach to pest control, relying on biological controls, crop rotation, resistant crop varieties, and targeted pesticide applications only when necessary. By reducing the overreliance on chemical inputs, these practices not only safeguard environmental health but also help preserve biodiversity, prevent pesticide resistance in pests, and promote long-term soil fertility. However, transitioning to such approaches often requires upfront investments in training, monitoring systems, and infrastructure, which many producers particularly small-scale farmers may find challenging without external support.

One strategy to encourage this transition involves creating certification programs that formally recognize and reward producers who adopt IPM and related sustainable practices. Much like existing certifications for organic or fair-trade products, a “low residue” or “sustainably grown” label could signal to consumers that the food they are purchasing was produced with a commitment to reducing pesticide use. This could provide a significant market advantage as consumer demand for “cleaner” and environmentally responsible food continues to grow. Retailers and food brands could further amplify this incentive by offering premium shelf space, marketing support, or even price premiums for certified products, creating a virtuous cycle that rewards sustainability throughout the supply chain.

To complement certification programs, public policies could provide additional incentives such as tax breaks, subsidies, or grants to support farmers and food companies in implementing IPM systems. Investment in extension services and technical assistance programs could also help disseminate knowledge and best practices, ensuring that both large

agribusinesses and smallholders can participate in and benefit from the shift toward sustainable agriculture. By aligning economic incentives with environmental and public health goals, these efforts would not only meet consumer expectations for safer, “cleaner” food but also strengthen the resilience of agricultural systems in the face of climate change and evolving pest pressures.

5. Conclusion

To conclude, pesticides are in supporting modern agriculture by boosting crop yields, controlling pests, and ensuring global food security. However, it also shows the complicated trade-offs between these benefits and the emerging health risks linked to pesticide residues in food. Evidence indicates that while most pesticide residues in food stay within established regulatory limits, long-term low-level exposures, especially in vulnerable populations like children and pregnant women, can cause serious health problems, including endocrine disruption, neurodevelopmental issues, reproductive disorders, cancer, and genetic damage. A significant consumer concern about pesticide residues is also often driven by limited scientific understanding and the mistaken belief that any detectable residue poses a high risk. Regulatory agencies, including the U.S. Environmental Protection Agency (EPA) and the Codex Alimentarius, have implemented safeguards such as Maximum Residue Limits (MRLs). Yet, enforcement gaps, differences in national standards, and inadequate public communication continue to erode consumer confidence.

Implications for Policy and Research

There is an urgent need for policy interventions that prioritize transparent and science-based risk communication. Policymakers should consider implementing residue labeling systems such as traffic light indicators or QR codes to provide consumers with accessible and transparent information on food safety. Strengthening monitoring and enforcement of MRLs, particularly in low-resource areas or settings, is essential to ensure compliance with international standards. Again, incentivizing the adoption of Integrated Pest Management (IPM) and other sustainable farming practices can reduce pesticide use without compromising agricultural productivity.

For researchers, there is a growing need to investigate the cumulative “cocktail effects” of multiple pesticide exposures, long-term health outcomes of chronic low-dose ingestion, and the effectiveness of public education strategies in improving risk perception. Research must also explore the socio-economic and cultural barriers to adopting sustainable agricultural practices globally.

Future Directions

Future efforts should focus on harmonizing international regulatory standards to reduce trade barriers and ensure global food safety. Enhanced collaborations between governments, scientists, and industry stakeholders are needed to foster innovations in pesticide alternatives and sustainable agriculture. Moreover, integrating pesticide education into school curricula and public health campaigns could promote scientific literacy and empower consumers to make informed choices. These actions are crucial for developing resilient food systems that safeguard human health while meeting the increasing demands of a growing global population.

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