Journal of Toxicological Studies 2024, 2(2), 1667.
https://doi.org/10.59400/jts.v2i2.1667

Review

The impact of pesticides: Assessing residue persistence, environmental contamination, and human health risks

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CITATION

Viancelli A, Comelli C, Nogara CM, et al. The impact of pesticides: Assessing residue persistence, environmental contamination, and human health risks. Journal of Toxicological Studies. 2024; 2(2): 1667. https://doi.org/10.59400/jts.v2i2.1667

ARTICLE INFO

Received: 29 August 2024
Accepted: 21 October 2024
Available online: 29 October 2024

Abstract: The intensification of agricultural practices to meet global food demand has led to extensive pesticide use, which poses significant challenges for food safety, environmental health, and human well-being. This narrative review provides a comprehensive analysis of the global use of pesticides in agriculture, focusing on the persistence of pesticide residues in food crops, their environmental impacts, and the associated health risks. Historically, pesticides have been integral to agricultural productivity, but their adverse effects have become increasingly clear. Notably, pesticide residues in food can pose serious health risks, particularly to vulnerable populations such as children and pregnant women. This review also discusses regional disparities in pesticide-related health outcomes, with a focus on Brazil. The findings underscore the urgent need for sustainable pest management practices, including organic farming and improved regulatory measures, to mitigate the adverse effects of pesticide use. By integrating these strategies, a more balanced and sustainable agricultural system can be achieved, safeguarding both human health and environmental quality.

Keywords: pesticide residues; environmental health; sustainable agriculture

1. Introduction

The intensification of agricultural practices, driven by the need to meet growing global food demand, has led to the extensive application of pesticides [1]. Pesticides have become an integral component of modern agriculture, applied to protect crops from pests, weeds, and diseases by killing or restricting the population expansion of some organisms [2]. While these pesticides have undoubtedly contributed to increased agricultural productivity, their widespread use raises serious concerns regarding their residues in food, environmental contamination, and potential health risks to humans [3,4].

The persistence of pesticide residues in vegetables and other food products poses a direct threat to consumer health. Numerous studies have documented the presence of these residues in market-ready products, often exceeding recommended safety levels [5–8]. Exposure can lead to adverse health effects, particularly in vulnerable populations such as children, pregnant women, and agricultural workers [9]. Beyond direct human exposure, pesticides also have significant environmental implications, contaminating soil, water, and non-target organisms, further complicating the assessment of their safety and long-term impacts [10–13].

Given the increasing awareness of their harmful effects on both the environment and human health, this review is significant as it provides a comprehensive assessment of the global use of pesticides, their persistence in food crops, and the associated health and environmental risks. By highlighting the alarming prevalence of pesticide residues and their potential impacts on vulnerable populations, this work aims to raise awareness among stakeholders, including policymakers and the agricultural community, about the critical need for safer pesticide management practices. Ultimately, this review serves as a call to action for adopting sustainable agricultural practices that safeguard human health and the environment.

2. Global use of pesticides in agriculture

The use of pesticides in agriculture has a long history that dates back to ancient civilizations where natural substances like sulfur, arsenic, and plant extracts were employed to protect crops from pests and diseases [14]. However, the advent of synthetic chemical pesticides in the mid-20th century marked a turning point in agricultural practices worldwide. The introduction of compounds such as DDT (dichlorodiphenyl-trichloroethane) and organophosphates revolutionized crop protection, leading to significant increases in agricultural productivity [15–17]. These chemicals quickly became the cornerstone of pest management strategies, allowing farmers to control various pests with efficacy. However, in 1962, Rachel Carson published the book "Silent Spring", highlighting the harmful effects of DDT on the environment and human health, which made some states prohibit the use of DDT [18].

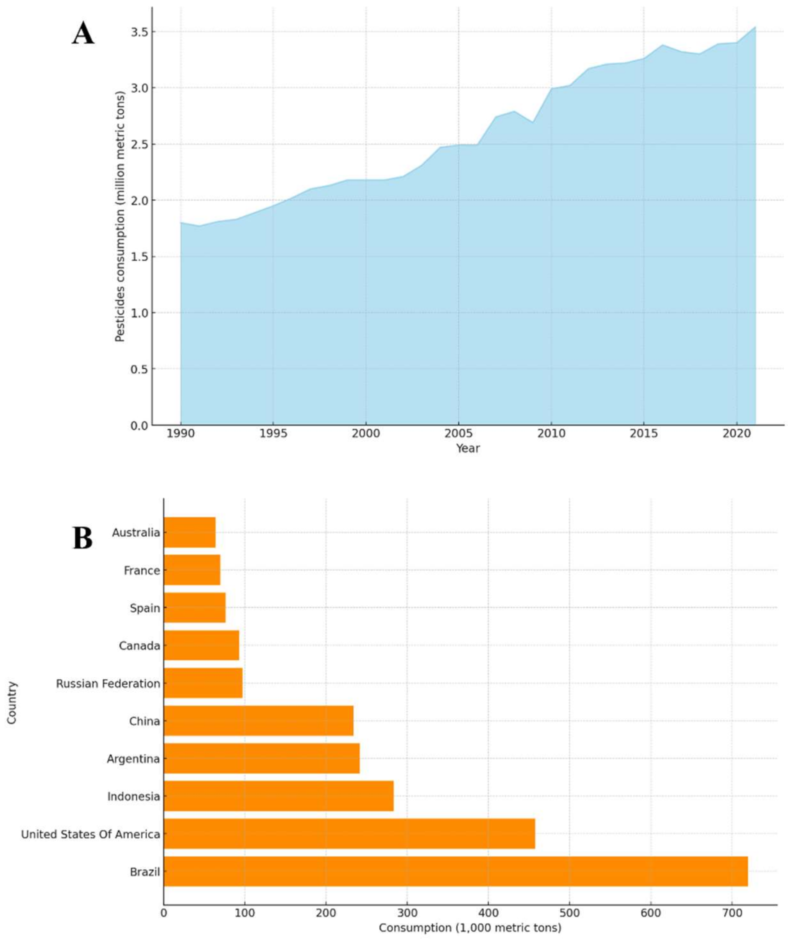

Figure 1. Pesticide consumption worldwide. **(A)** and country ranking of consumption of pesticides; **(B)** from 1990 to 2021.

The Green Revolution of the 1960s further accelerated the global adoption of other pesticides, such as high-yield crop varieties, coupled with the intensive use of agrochemicals, which were promoted to combat food insecurity in developing countries [14]. This period saw a dramatic increase in pesticide production and usage, particularly in countries with rapidly expanding agricultural sectors [19].

In recent decades, the global pesticide market has continued to grow (**Figure 1A**) [20]. Brazil, the United States, and Indonesia were the biggest consumers of pesticides (**Figure 1B**). Brazil applied 719,507 tons of pesticides in 2021, followed by the United States (457,385 tons) and Indonesia (283,297 tons). Herbicides, insecticides, and fungicides remain the most commonly used classes of pesticides, with glyphosate, in particular, becoming the most widely applied herbicide globally [21].

Considering the vast quantities of pesticides applied annually, it is important to evaluate their potential impacts on living organisms across all environmental compartments.

A study by Maggi et al. [22] mapped the global indexes of pesticide hazards, population exposure, and human intake dose in 133 nations. All the indexes showed hotspots in the Americas, Asia, and Europe; however, it is worth highlighting that in Europe (EU27), the legislation is strict on pesticide use. The study also revealed that 1.7 billion people live near pesticide application areas with pesticide loads above 100 kg km-2 year-1, 2.3 billion exceed the acceptable pesticide intake, and 15% of them exceed by 10 fold.

The study by Tang et al. [23] reported that 64% of global agricultural land is at risk of pesticide pollution involving more than one active ingredient. Additionally, 31% of this land is at high risk, meaning pesticide residues exceed no-effect concentrations by three orders of magnitude. Among the high-risk areas, 34% are located in regions of high biodiversity, 5% in water-scarce areas, and 19% in low- and lower-middle-income countries. Watersheds in South Africa, China, India, Australia, and Argentina were identified as high-concern regions due to high pesticide pollution risk, rich biodiversity, and water scarcity. This study stands out by evaluating multiple active ingredients and integrating risks across different environmental compartments on a global scale.

The widespread use of pesticides continues to raise significant concerns regarding environmental pollution and public health risks worldwide. These findings underscore the urgent need for more stringent regulations, better management practices, and global collaboration to mitigate the impacts of pesticide pollution and safeguard both ecosystems and human populations.

3. Pesticide residue persistence in vegetables

Pesticide residues in food crops, particularly vegetables, are a significant concern due to their potential impacts on human health [24]. The persistence of these residues is influenced by a complex interplay of factors that determine the length of time that a pesticide remains in or on the plant after application [25,26]. Every year, the Environmental Working Group (EWG), a nonprofit organization from the USA, publishes a list of the 12 vegetables with the most pesticide residues [27]. In 2024, the vegetables were: strawberries (1°), spinach (2°), kale, collard and mustard greens (3°), grapes (4°), peaches (5°), pears (6°), nectarines (7°), apples (8°), bell and hot peppers (9°), cherries (10°), blueberries (11°), and green beans (12°) [27].

One of the primary factors influencing pesticide residue persistence is the chemical nature of the pesticide itself. Pesticides can vary widely in their stability, solubility, and volatility, which directly affect their behavior in the environment and within the plant. For instance, highly lipophilic pesticides tend to accumulate in the waxy cuticle of plant leaves, leading to longer persistence. In contrast, hydrophilic pesticides may be more readily washed off by rain or irrigation; however, they can also be absorbed more easily by the plant's roots and transported throughout its tissues [28].

The mode of application influenced the residue levels. Foliar applications, in which pesticides are sprayed directly onto the leaves, often result in higher residue levels on the surface of the vegetable. A study conducted by Juraske et al. [29] evaluated the application of the insecticide imidacloprid in tomatoes, and the results showed that the total residues were up to five times higher in plants treated by foliar spray application than by soil irrigation.

In contrast, systemic pesticides, which are absorbed by the plant and translocated throughout its tissues, can lead to residues within the plant itself [30]. The timing of the application relative to the harvest period is another key factor; pesticides applied closer to harvest are more likely to leave residues that persist until the crop reaches the consumer [29].

Environmental conditions such as temperature, humidity, and sunlight also significantly impact pesticide residue persistence [31]. Higher temperatures can accelerate the degradation of some pesticides, reducing their persistence, while others may become more stable under these conditions. Ultraviolet (UV) radiation from sunlight can break down certain pesticide molecules, but some compounds may degrade into more toxic byproducts, complicating residue management [31]. Soil composition and microbial activity further influence the degradation or persistence of pesticides, particularly for those absorbed through the roots [32].

Vegetable characteristics, such as the type of crop, growth stage, and presence of protective structures like leaves or husks, also affect residue persistence [33]. Leafy vegetables, for example, often have higher residue levels due to their large surface area and exposure to pesticide sprays [24]. Root vegetables, on the other hand, may accumulate residues differently because pesticides in the soil can be absorbed directly by the roots [34].

4. Pesticide contamination of soil and water

When pesticides are applied to crops, a portion inevitably reaches the soil, where it can either be absorbed by plants, leach into groundwater, or run off into surface waters such as rivers, lakes, and streams [34]. The extent of soil and water contamination depends on various factors, including the chemical properties of the pesticide, soil composition, climate conditions, and agricultural practices [35].

In soil, pesticides can persist for a long time depending on their degradation rates, which are influenced by factors such as temperature, moisture, and microbial activity [36]. Some pesticides, particularly those with high persistence, pose a risk of accumulation over time, affecting soil health and fertility [37]. Additionally, pesticides can bind to soil particles and be transported by erosion, further spreading contamination to adjacent ecosystems [35].

A study by Silva et al. [38] investigated the contamination by pesticide residues in soil collected from 11 countries members of the European Union. The results showed that 80% of the tested soils were contaminated by pesticide residues in a total of 166 different pesticide combinations [38].

Water resources are particularly vulnerable to pesticide contamination from runoff from agricultural fields [39]. A study by Andrade et al. [40] evaluated river water before and after rainfall during the pesticide application in agricultural regions of Argentina. The results showed that pesticide concentrations in the rivers increased immediately after rainfall events. However, the authors also observed that pesticide concentrations can change depending on the crop life cycle, the pesticide solubility, the area slope, and the percentage of riparian forest [40].

This contamination poses risks not only to aquatic ecosystems but also to human populations that use these water sources for drinking and irrigation [1]. Pesticides in water can persist in the environment, sometimes forming harmful byproducts that exacerbate their toxic effects [41]. The contamination of water resources by pesticides is a critical concern because it can lead to the bioaccumulation of toxic substances in aquatic organisms, which may then be transferred up the food chain, ultimately affecting human health [1].

Clasen et al. [42] evaluated the bioaccumulation of five pesticides during fish growth in consortium with rice. The results showed that after 100 days of exposure, the pesticides lambda-cyhalothrin and tebuconazole bioaccumulated in carp muscles. Additionally, pesticides induce oxidative stress on fish, indicating the potential risk to other organisms [42].

The ecological consequences of pesticide accumulation underscore the need for sustainable pest management practices that minimize environmental contamination and protect biodiversity. Strategies such as integrated pest management, organic farming, and the development of less persistent and targeted pesticides are essential for reducing the environmental impact of pesticide use and ensuring the health of ecosystems [43].

5. Effects on non-target species and biodiversity

Pesticides are designed to target specific pests, but their effects often extend to non-target species, including beneficial insects, plants, and animals. This non-selectivity can have severe consequences for biodiversity, disrupting ecological balances and leading to the decline of important species [44]. For example, pollinators such as bees and butterflies, which are important for the reproduction of many plants, can be affected by pesticide exposure, leading to declines in their populations [45,46]. Similarly, predators and parasitoids that naturally control pest populations can be adversely affected, reducing the effectiveness of biological pest control and potentially leading to pest outbreaks [47].

Aquatic ecosystems are particularly sensitive to pesticide contamination. Fish, amphibians, and aquatic invertebrates can be directly affected by pesticide exposure, leading to reduced survival, reproductive failure, and altered behavior [1]. The loss of these species can disrupt food webs and cause cascading effects throughout the ecosystem. Downing et al. [48] observed the impact of pesticides in a mesocosmic aquatic ecosystem, where zooplankton richness, diversity, abundance, and oxygen concentrations decreased and remained with significant differences even after 40 days.

6. Pesticide occurrence in the atmosphere

The atmospheric presence of pesticides has become an increasingly critical issue [49]. Pesticides can enter the atmosphere through various pathways, including volatilization during and after application, drift during aerial spraying, and atmospheric deposition from agricultural fields [50]. Once in the atmosphere, these chemicals can be transported over considerable distances, often affecting ecosystems and communities far from their original localization [51].

Recent studies have detected a range of pesticides in air samples collected from rural and urban areas [49,52]. For instance, volatile organic compounds such as chlorpyrifos and diazinon have been identified in the air, even in regions with no direct agricultural activity [53]. This phenomenon raises significant concerns about the potential for human exposure to these toxic substances, particularly among populations living near agricultural fields [54].

Factors influencing the volatilization and atmospheric transport of pesticides include temperature, humidity, and wind speed [50]. Higher temperatures can enhance volatilization rates, increasing the likelihood of pesticide dispersal into the air. Additionally, wind can facilitate the movement of pesticide particles, thereby contributing to their spread over large areas [50].

Atmospheric deposition is another important mechanism through which pesticides can pollute land and water resources. Pesticides in the atmosphere can be removed by precipitation, which leads to the contamination of soil and surface water [55]. This process, often referred to as “pesticide rain”, can lead to the accumulation of harmful chemicals in ecosystems, affecting plant and animal life [52]. For example, studies have shown that pesticides can be found in rainwater collected in agricultural regions, raising concerns about the long-term effects of pesticides on soil health and water quality [56,57].

A previous study identified the widespread presence of organochlorine pesticides in the air of urban areas in Southeast Brazil, particularly in the regions of Rio de Janeiro and São Paulo [58]. The most prevalent organochlorine pesticides detected were Σ-HCH and Σ-DDT, both still registered for domestic sanitation purposes in Brazil. Concentrations of these pollutants tended to be higher during the summer months [58]. This seasonal fluctuation suggests that environmental conditions, such as increased temperatures, may enhance the volatilization and dispersion of these chemicals, further elevating the exposure risk in urban areas. A key aspect of the research was the assessment of health risks, specifically cancer risks associated with inhaling organochlorine pesticides. The findings indicated that individuals living in the studied regions face increased cancer risks, with infants and children showing the highest vulnerability [58].

Another study conducted in both urban and rural areas of São Paulo, Brazil, evaluated pesticides associated with particles measuring 2.5 micrometers or smaller. The findings revealed that in rural areas, the most frequently detected pesticides were λ-cyhalothrin, kresoxim-methyl, and atrazine. In contrast, permethrin and malathion were most commonly found in urban and industrial locations [59].

The impact of atmospheric pesticide occurrence is complex. Understanding the dynamics of pesticide occurrence in the atmosphere is essential for developing effective monitoring and regulatory strategies aimed at protecting public health and the environment.

7. Human health risks from pesticide exposure

The initial enthusiasm for these "miracle" chemicals soon gave way to concerns about their environmental and health impacts [60]. Pesticide exposure can cause acute and chronic health effects, depending on the level, duration, and frequency of exposure. Acute exposure typically occurs through direct contact with pesticides during application, accidental ingestion, or inhalation. The symptoms of acute pesticide poisoning can range from mild, such as headaches, and nausea, to severe, including respiratory distress, convulsions, and even death in extreme cases [61].

Organophosphates and carbamates, which are commonly used insecticides, are notorious for their acute toxicity, as they inhibit acetylcholinesterase, an enzyme essential for normal nervous system function [62]. As a consequence, the patient presents with muscle paralysis affecting particularly upper-limb muscles, neck flexors, and cranial nerves some 24–96 h after organophosphates exposure and is often associated with the development of respiratory failure [62].

Chronic exposure to pesticides, often resulting from prolonged, low-level exposure, can lead to various long-term health issues. These conditions may include respiratory problems, skin disorders, and chronic neurological conditions [61]. Chronic pesticide exposure has been associated with reproductive and developmental effects, such as reduced fertility, congenital disabilities, and developmental delays in children [63]. The latency period between exposure and the manifestation of chronic conditions can make it challenging to establish direct causal relationships, further complicating risk assessment and management.

Considering that Brazil is the largest consumer of pesticides, below is reported data from intoxication by pesticides, which most frequently occurs by contact during agricultural practices. **Figure 2** provides data on intoxication cases around Brazilian states over the years 2013 to 2023 reported by the Health Ministry—DATASUS system (https://datasus.saude.gov.br/).

It is possible to conclude that states such as Minas Gerais, São Paulo, and Paraná consistently show the highest notification rates across all years. These states are major economic centers with significant agricultural and industrial activities, which could explain their higher levels of reporting. The infrastructure and resources available in these states may contribute to better data collection and reporting mechanisms. In contrast, states such as Acre, Amapá, and Roraima show significantly lower notification rates. These regions are characterized by lower population densities and more remote locations, which could hinder data collection and reporting. The low notification rates may not accurately reflect reality but rather highlight the challenges in monitoring and reporting in these areas.

The observed disparities suggest the need for more equitable distribution of resources and efforts to improve data collection in underreported regions. Enhancing monitoring infrastructure in less developed states could lead to more accurate and comprehensive data.

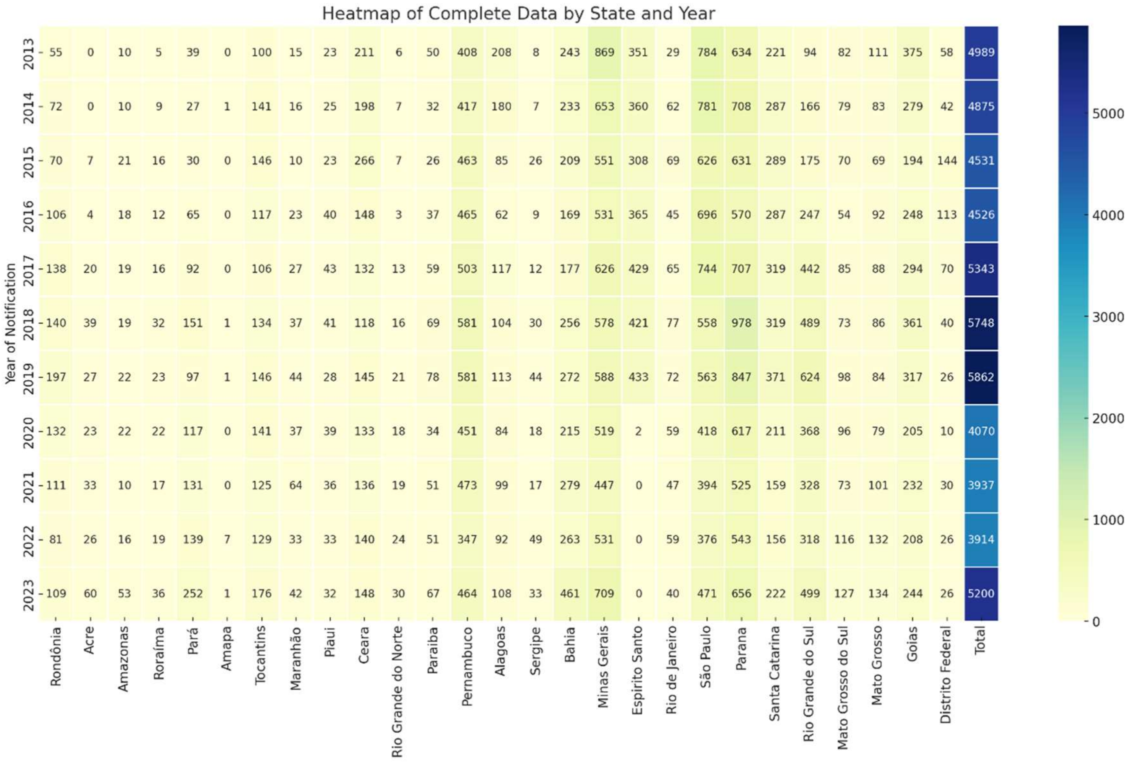

Figure 2. Occurrence of notification by intoxication with pesticides used in agriculture reported in Brazilian States from 2013 to 2023. Source: DATASUS.

Figure 3 illustrates deaths across Brazil from 2013 to 2023. The analysis reveals significant regional disparities that highlight the varying impacts of health-related challenges across the country. Pernambuco, in the Northeast region, stands out with the highest number of deaths, accounting for 382 fatalities. In the southeast region, São Paulo and Minas Gerais have reported 189 and 172 deaths, respectively. The Southern region, particularly Paraná, has a high number of deaths, with 231 fatalities reported. In contrast, the Northern and Central-Western regions, while showing lower absolute numbers of deaths, reflect concerning trends in states like Rondônia (89 deaths) and Goiás (45 deaths).

The high mortality rate could be attributed to a combination of factors, including socioeconomic conditions, healthcare infrastructure, or poor careful practices during pesticide application [64]. In any event, this concentration of deaths underscores the need for targeted public health interventions to address the underlying causes.

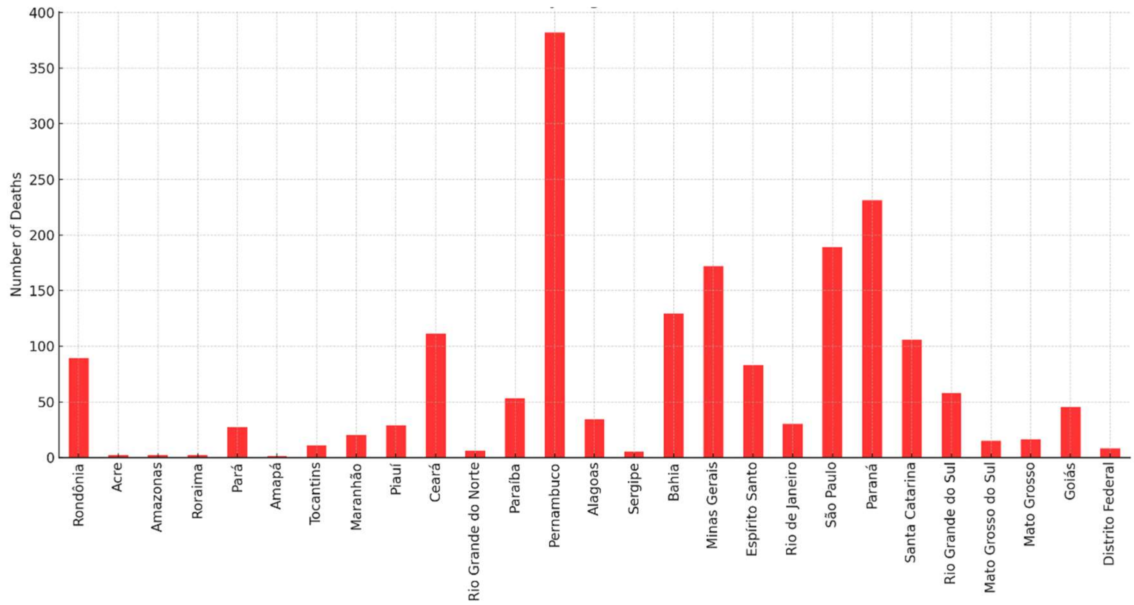

Figure 3. Occurrence of deaths caused by intoxication by pesticides of agricultural use in Brazil, from 2013 to 2023.

Agricultural workers, pesticide applicators, and residents of rural areas near agricultural fields are among the most at-risk groups due to their frequent and direct contact with pesticides [65]. Occupational exposure to pesticides can be particularly hazardous because workers may be exposed to concentrated forms of these chemicals, often without adequate protective measures [66]. Studies indicate that agricultural workers are at a high risk of various chronic conditions, including cancer, mental, neurological, endocrine, renal, auditory, respiratory, and autoimmune diseases. Additionally, they are susceptible to subclinical effects, such as genetic damage and biochemical alterations, as well as clinical signs and symptoms of acute intoxication. These studies also highlight several limitations, particularly in the assessment of exposure and outcomes, as well as in study design and sampling [67,68].

In their study, Pignati et al. [69] reported that pesticide workers from Mato Grosso State (Brazil) were 20 to 49 years old, often lacked formal qualifications, and were employed as machine operators, mechanics, and agricultural workers. Additionally, they live less than 500 meters from agricultural fields and handle herbicides. Additionally, Pluth et al. [70] reported a higher incidence of cancer in people living in rural areas with extensive use of pesticides.

Children are another vulnerable population because of their developing bodies and behaviors that increase their exposure risk, such as playing on treated surfaces or consuming residues from food. Their metabolic pathways are also less developed, making them less capable of detoxifying and eliminating pesticides from their bodies [71]. Pregnant women are similarly at risk because pesticide exposure during pregnancy can affect fetal development, leading to adverse birth outcomes such as low birth weight, preterm birth, and congenital disabilities [72].

8. Strategies to reduce pesticide risks

Organic and sustainable farming practices play an important role in reducing pesticide risks by minimizing or eliminating the use of synthetic pesticides and promoting ecological balance in agricultural systems [73]. In Brazil, the Fazenda Malunga, located in the Federal District of Brazil, serves as a model for sustainable agriculture through its production of organic vegetables. Established in the 1980s, the farm has become a leader in pesticide-free food production, supplying fresh produce to various markets across the Central-West region of Brazil. The farms' practices emphasize environmental stewardship, social equity, and economic viability, aligning with the principles of organic farming. Furthermore, Fazenda Malunga contributes to environmental education by offering guided tours that educate visitors about organic agriculture and sustainable practices [74].

One of the primary benefits of organic farming is the reduction in pesticide residues in food and in the environment, which directly translates into lower health risks for consumers and reduced environmental contamination. By fostering natural pest control mechanisms, such as the presence of beneficial insects and microorganisms, organic farming reduces the reliance on chemical interventions. Additionally, organic practices often lead to improved soil health, which can enhance crop resilience to pests and diseases, further decreasing the need for pesticides.

The widespread use of pesticides in modern agriculture, while instrumental in enhancing crop yields and combating pests, presents significant challenges related to food safety, environmental contamination, and human health. The persistence of pesticide residues in food and the environment poses direct health risks to consumers, especially vulnerable groups. The widespread contamination of soil and water resources further complicates the issue, resulting in ecosystem degradation and potential long-term impacts on biodiversity.

Addressing pesticide contamination necessitates not only the implementation of regulatory measures but also the exploration of innovative remediation techniques. Among these, the use of magnetic graphene oxide (MGO) has gained significant attention owing to its superior adsorption properties and ease of separation from contaminated media [75]. MGO exhibits a high surface area and functional groups that enhance its affinity for various pesticide molecules, enabling its effective removal from both water and soil matrices. The incorporation of magnetic nanoparticles into graphene oxide facilitates the rapid separation of the adsorbent using an external magnetic field, significantly reducing the time and labor associated with traditional filtration methods [76].

Recent studies have demonstrated the efficacy of MGO in adsorbing common agricultural pesticides, such as glyphosate and organophosphates [77], with its adsorption capacities surpassing those of conventional adsorbents. Furthermore, the functionalization of MGO can be tailored to enhance its selectivity for specific pesticide classes, improving its overall efficiency in real-world applications.

In addition to MGO, alternative methods, such as phytoremediation, which utilizes specific plant species to uptake and detoxify pesticides from contaminated soils, show promise. Plants like sunflowers have been identified as effective pesticide residue accumulators, enabling their safe disposal through harvesting [78]. Furthermore, advanced oxidation processes, including ozonation and photocatalysis, use reactive oxygen species to degrade pesticide contaminants into less harmful byproducts, thus enhancing the safety of agricultural runoff [79].

Collectively, these innovative approaches, including the use of magnetic graphene oxide, provide strategies for addressing pesticide residues. They not only mitigate the environmental and health impacts of pesticide use but also contribute to the development of sustainable agricultural practices. The integration of these technologies could serve as a vital component of comprehensive pesticide management programs, ensuring the safety of food systems and the protection of ecological health.

Addressing these concerns requires a multidisciplinary approach that includes the adoption of sustainable agricultural practices, such as organic farming. Efforts to improve pesticide management, enforce safety regulations, and enhance public awareness are essential to mitigate the adverse effects associated with pesticide use. By integrating these strategies, we can work toward a more balanced and sustainable agricultural system that protects both human health and the environment.

Conflict of interest: The author declares no conflict of interest.

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