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REVIEW

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Comprehensive insights into pesticide residue dynamics: unraveling impact and management

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Abstract

The imperative use of pesticides for enhancing agricultural productivity has become inevitable. Unfortunately, the unregulated and indiscriminate application of these pesticides extends beyond the intended target areas, with residues persisting for months to even years. This lack of precision and information has triggered widespread pest outbreaks, posing significant health risks to both humans and other organisms due to pesticide residues in food. The presence of even trace amounts of these residues has emerged as a major impediment to international trade in food commodities. To address these challenges and align with sustainable practices, the article highlights the urgent need for controlled pesticide techniques, including organic farming, safe harvest indices, and bioremediation, which are crucial aspects of mitigating admixed micropollutants in the environment. The discussion covers the impact of pesticides on food quality, effective residue management, and the vital role of regulatory bodies. Drawing from diverse sources, the work seeks to provide a concise yet comprehensive overview and solutions to the challenges of pesticide management.

Highlights

- Highlights unintended consequences of unregulated pesticide use and health risks.
- Pesticide residues impede trade and compromise agricultural product safety.
- Persistent residues cause pest outbreaks, threatening human and environmental health.
- Advocates organic practices, safe harvest indices, and bioremediation for mitigation.
- Tackles pesticide challenges to safeguard food security and promote sustainability.

Keywords Pesticide residues, Food, Determinants, Molecular targets, Bioremediation, Human health

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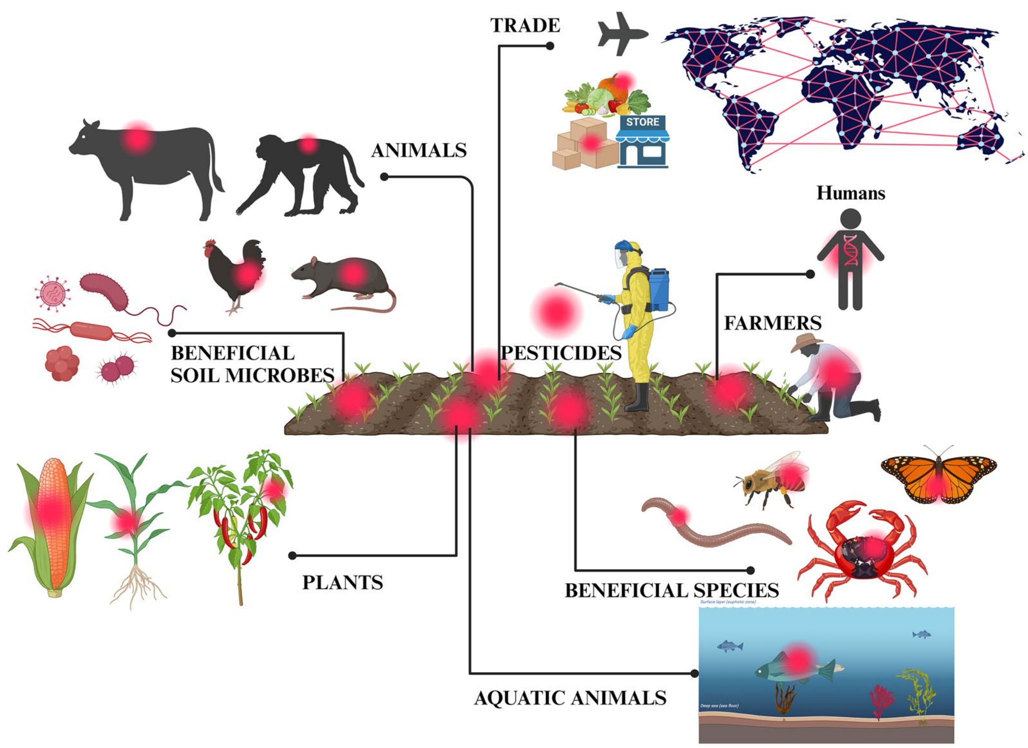
Graphical abstract



Introduction

Global estimates reveal that approximately 1.8 billion people are engaged in agriculture, with most relying on pesticides to protect food supplies and commercial crops. To meet the demands of a growing global population and maintain a stable food supply, pesticide use remains essential [1, 2]. Additionally, pesticides are utilized in non-agricultural sectors, including public health programs, sports grounds, and public gardens. However, excessive use of these chemicals can adversely affect both environmental and human health [3]. Accumulated pesticide residues in agro-food sources are a primary cause of chronic or acute health risks [4]. While pesticides are widely regarded as essential for preventing crop loss and ensuring food security, ongoing discussions emphasize the need to evaluate not only their necessity but also the types of pesticides used, prioritizing options with lower environmental impact and toxicity. Recent studies highlight that alternative pesticides, including biopesticides and integrated pest management solutions, may reduce dependency on traditional synthetic chemicals while still achieving effective pest control [4]. Short-term exposure to pesticides can lead to acute toxicity and skin irritation, whereas long-term exposure has been associated with allergies, liver dysfunction, immune system disorders, reproductive complications, and peripheral neuropathy. Systemic toxicity has also been linked to carcinogenic and teratogenic effects, cardiovascular and endocrine disorders, and potentially fatal outcomes in animals [5–8]. Increasing incidences of pests, diseases, and weeds have contributed to crop losses, mortality, and labor-intensive pest control efforts. Therefore, a scientifically guided approach to pesticide application is critical for effectively managing these challenges [9, 10]. Chemical pesticides, which have been instrumental in boosting crop production, remain integral to modern agriculture. When applied responsibly, these pesticides reduce stored grain losses, control pest infestations, and enhance overall human welfare [11, 12]. According to the United States Code of Federal Regulations, a pesticide is defined as any compound or mixture intended for use as an insecticide, defoliant, plant growth regulator, or desiccant [3]. Historically, various chemicals have been employed to control pests effectively [4]. India, for example, ranks among the top pesticide producers in Asia, with annual organochlorine pesticide production nearing 90,000 tons [5]. Currently, agriculture consumes about 2.16 million tons of mineral fertilizers and between

64,000 and 65,000 tons of plant protection chemicals annually, emphasizing the essential role of pesticides in food production and pest management [7, 8]. It should be noted that while 'pesticide use' and 'pesticide consumption' are commonly referenced indicators, they do not fully account for the environmental impact or toxicological properties of the pesticides applied. These indices can be misleading as they overlook variations in toxicity levels, persistence, and bioaccumulation potential of different pesticide compounds. A more comprehensive approach would consider these factors alongside usage data to accurately reflect potential risks to human health and the environment.

Modern agriculture employs a wide range of pesticide products, including insecticides, fungicides, herbicides, miticides, nematicides, rodenticides, and molluscicides [13]. Insecticides alone can be classified into four primary groups based on their chemical structure: neonicotinoids, carbamates, organochlorines, and organophosphates [14]. Additionally, a diverse array of other compounds, such as amides, benzimidazoles, copper and mercury-based agents, nitro compounds, triazine herbicides, uric acid, ethylene dibromide, phthalamides, hormones, bipyridyls, and sulfur compounds, are also used in pest control [15]. This diversity highlights the complexity of modern pest management strategies. In this context, the detection of pesticide residues and their metabolites in food commodities is crucial [16]. Regulatory frameworks governing pesticide usage have had notable negative implications for food security, creating setbacks in this critical area. In response, protocols have been established to ensure responsible pesticide use [17, 18]. Despite the efforts of regulatory bodies to restrict pesticide markets, these compounds remain among the most pervasive environmental pollutants globally. The human health impacts of pesticide exposure are highly debated, with some studies linking chronic exposure to neurological disorders, endocrine disruption, and cancer. However, the European Food Safety Authority (EFSA) has conducted assessments, which argue that under current regulations, pesticide residues in food are unlikely to pose significant health risks. This review examines the latest data and adds to the ongoing discussion by evaluating gaps in regulation and pesticide management practices.

This review addresses the critical need for enhanced pesticide management by analyzing the impact of pesticide use on food quality, residue management, and regulatory frameworks. Although the topic of pesticide dynamics has been widely studied, our work uniquely highlights the gaps in existing regulatory practices, identifies the latest challenges posed by emerging pesticide compounds, and proposes practical solutions to support sustainable management practices. Drawing on recent methodologies and motivations in environmental and food safety research, this review provides an updated, comprehensive overview of current practices, challenges, and innovative strategies for effective pesticide management.

Review methodology

To identify and address research gaps in pesticide dynamics and management, a comprehensive meta-analysis of relevant literature was conducted. This review systematically examined previous studies spanning the last two decades, with a focus on pesticide toxicity, environmental impact, residue persistence, and regulatory practices. Key databases, including Web of Science, PubMed, and Scopus, were searched using terms such as "pesticide residue management", "pesticide toxicity dynamics", and "environmental pesticide impact", yielding a wide range of peer-reviewed articles. Inclusion criteria for this review were based on studies presenting empirical data, insights into regulatory approaches, or recent advancements in pesticide degradation and remediation. Each selected study was assessed for contributions to understanding pesticide persistence in environmental matrices, regulatory challenges, and management strategies. Through qualitative and quantitative synthesis, this meta-analysis identifies critical research gaps, such as the need for advanced remediation techniques, limitations of current residue regulations, and underexplored pesticide impacts on non-target organisms and ecosystems. This approach allows for a structured assessment of existing knowledge while highlighting opportunities for future research and policy innovation.

Understanding pesticide fate in ecosystems: sources, stability, and environmental risks

The fate of pesticides in ecosystems is predominantly shaped by abiotic transformations linked to their physicochemical properties [19, 20]. These inherent characteristics enhance pesticide stability, minimizing losses, while their chemical structures play a significant role in determining their persistence in soil and the broader environment [21]. Pesticide residues in consumer goods arise from four primary sources: (i) agricultural applications, (ii) post-harvest treatments, (iii) residues in imported products, and (iv) the release of banned pesticides into the environment [22, 23]. Improper pesticide use can lead to environmental risks, despite their critical role in preventing groundwater contamination, safeguarding human and livestock health, and maintaining disease-free environments. However, challenges remain due to widespread usage and inadequate waste management strategies, necessitating urgent attention to pesticide-related concerns [24–26]. Pesticides enter various environmental compartments depending on their chemical nature, soil composition, crops, and ecological conditions. Estimates suggest that up to 50% or more of applied pesticides may evaporate into the atmosphere [27, 28]. Understanding pesticide movement in the environment is vital for sustainable agriculture and environmental conservation.

One major pathway is aerial drift, where wind transports pesticide sprays or dusts, potentially contaminating non-target areas and posing significant challenges [29]. Runoff, another critical pathway, occurs during rainfall or irrigation, where water carries pesticides from treated fields into nearby surface water bodies, threatening aquatic ecosystems and necessitating vigilant oversight [30]. Groundwater contamination, a serious concern, results from pesticides percolating through soil and reaching groundwater, potentially compromising drinking water supplies and causing long-term environmental harm [31, 32].

Volatilization and atmospheric transport are also key factors in pesticide fate. After application, pesticides can volatilize, travel over long distances, and deposit in remote areas, increasing their presence in ecosystems far from the source [33, 34]. Biological uptake further complicates this dynamic, as plants can absorb pesticides, leading to translocation within plant tissues and impacting harvested crops, posing risks to consumers [35]. Vapor drift, the transition of pesticides from liquid to vapor, allows for off-target deposition, emphasizing the need for effective mitigation strategies [36]. In some cases, pesticide efficacy on target organisms may diminish, inadvertently harming non-target species [24]. Additionally, insecticides can be transported within the environment, contributing to contamination [37], as shown in Table 1.

The complexity of pesticide fate in the environment arises from the interplay of various processes. It is clear that pesticides are transported and deposited across different environmental compartments [38]. However, significant uncertainties persist. Atmospheric deposition involves both dry deposition (direct settling onto surfaces like water and soil) and wet deposition (precipitation of particles and interception of gases). Once deposited, these compounds migrate until they reach their permanent sink [39].

Pesticide evolution within soil follows a multi-phase partitioning mechanism involving gaseous, solid, and liquid states [40] (Fig. 1). Degradation within the soil influences vertical diffusion [41]. Pesticides, when present as gases or bound to particles, can transition into the

Table 1 Pesticide travel distances and environmental impact as adapted from Boonupara et al. [37]

Pesticide type	Travel distance	Environmental impact	Conditions influencing travel
Organophosphates	Up to 10 km	Contamination of nearby water bodies; impacts on aquatic life	Wind speed, soil texture
Organochlorines	50–100 km	Bioaccumulation in wildlife, affecting birds and fish populations	Soil pH, temperature
Carbamates	5–20 km	Groundwater contamination; impacts on drinking water quality	Rainfall, irrigation practices
Neonicotinoids	Up to 5 km	Pollinator decline (bees, butterflies); impacts on plant reproduction	Wind conditions, plant cover

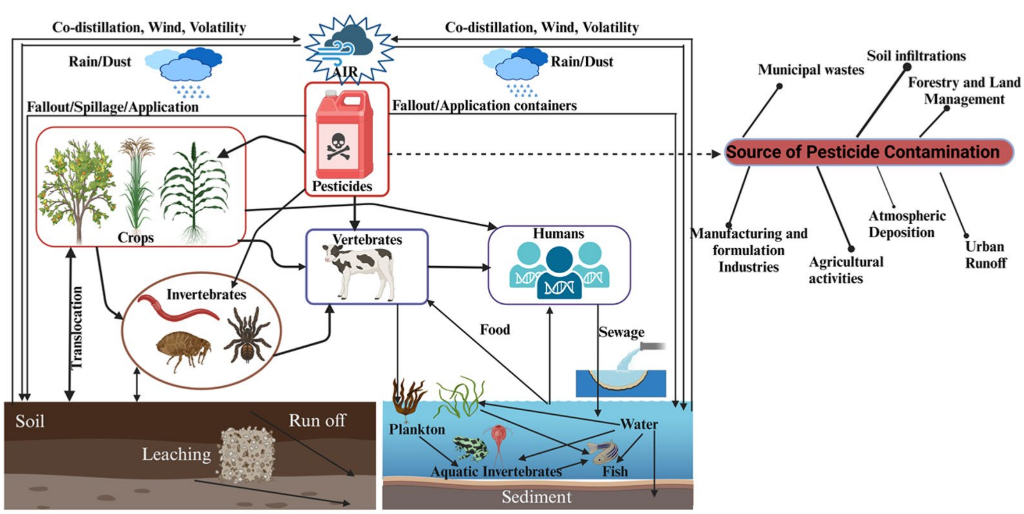


Fig. 1 Transport of pesticide in the environment as adapted and improved from Gavrilescu [40]. Figures created using BioRender software

aqueous phase through cloud scavenging [42, 43]. This process illustrates the potential for long-distance atmospheric transport, facilitating continuous pesticide movement across environmental systems.

Impact of pesticide residues on human health and ecosystem sustainability: sources, transport, and bioaccumulation

The widespread presence of pesticide residues in the environment, food products, and living organisms poses a significant threat to both human health and ecosystem sustainability. These residues are frequently found in various agricultural products, such as fruits, vegetables, cereals, and animal products [44]. Beyond agriculture, pesticides often enter surface water bodies through runoff and leaching, where they can harm aquatic ecosystems and degrade water quality [45]. Bioaccumulation, where pesticide residues accumulate in organisms like plants, animals, and microorganisms further disrupts ecosystems, impacts food chains, and poses risks to human health [46]. Additionally, in urban and residential areas, pesticide residues from pest control measures can enter the environment through runoff, affecting non-target species, including pets and humans [47]. Pesticides have been detected in farming regions worldwide, in soil, air, water, and even precipitation [48], and are found in remote areas where pesticide use is nonexistent [49]. Persistent organochlorine compounds such as DDT, aldrin, dieldrin, chlordane, toxaphene, and hexachlorocyclohexanes (HCHs) have been discovered in rainwater year-round. Notably, these compounds are not only detected in heavily treated agricultural regions, but also in remote geographical locations, such as the polar Arctic. This highlights the global nature of pesticide residue dispersion, with international trade contributing to their spread, necessitating strict adherence to international standards and regulations [50]. The emergence of new pesticide compounds and their metabolites further complicates the monitoring and management of residues, emphasizing the need for ongoing research in this area [51]. Atmospheric movement and accumulation serve as key pathways for the long-distance transport of pesticides, particularly insecticides, into remote regions [52, 53]. Comprehensive documentation of pesticide residues is essential for evaluating their distribution, presence, and potential impacts on both the environment and human health, as well as on food safety. Since the 1970s, industrialized nations have heavily relied on pesticides in both agriculture and vector control, making an understanding of their atmospheric movement crucial. Qualitative data on pesticide loads in the atmosphere are vital for developing mitigation strategies [54]. Reports indicate that certain organochlorine pesticides, including diazinon, chlorpyrifos, malathion, and parathion, are more prevalent in the air and rain than other pesticide groups [55, 56]. Additionally, systemic herbicides like atrazine have shown higher concentrations in forest canopies compared to agricultural lands, likely due to a filtering effect that allows for greater chemical adsorption during dry periods, followed by wash-off during precipitation [55]. Data also reveal that forests accumulate higher levels of pesticides than foliage, highlighting the deposition rates of these chemicals [57]. This growing body of evidence underscores the escalating use of pesticides and the substantial risks they pose to the environment and economy. It is clear that pesticides not only impact the areas where they are applied, but also extend their influence to non-target regions and species, contributing to broader environmental damage [58].

Pesticide residues as trade barriers: implications for agricultural exporters and international policy responses

Impact of pesticide residues on trade

International trade plays a crucial role in supporting the livelihoods of farmers and those involved in the food supply chain. It provides a global solution to food security, particularly in regions facing environmental challenges, while offering consumers diverse product choices. This, in turn, contributes to the economic well-being of consumers, industries, and agricultural workers [59, 60]. However, the presence of pesticide residues in food commodities presents significant obstacles in international trade, often leading to the rejection of products by importing countries [61]. To mitigate the impact of pesticide residues on exported goods, it is imperative for countries to adopt and enforce stringent regulatory measures. Promoting sustainable agricultural practices, alongside investments in research and education to develop safer pest control alternatives, are key strategies for addressing this issue [62, 63]. Furthermore, international cooperation is essential in harmonizing pesticide standards and ensuring a unified commitment to global food safety. The repercussions of pesticide residues in traded commodities are substantial for both exporting and importing nations. In recent years, maximum residue levels (MRLs) have become increasingly critical in shaping agricultural trade policies, influencing food security, and regulating international commerce (Table 2). Consequently, the ability to engage in trade can be significantly affected by differing pesticide residue regulations across countries. The World Trade Organization (WTO) acknowledges the right of each country to implement measures aimed at protecting human, animal, and plant health. Pesticide residue regulations are often encompassed within Sanitary and Phytosanitary

Table 2 Maximum residue levels (MRLs) in food samples over time

Food type	Pesticide	MRL (2010)	MRL (2020)	Health implications
Wheat	Glyphosate	0.3 ppm	0.5 ppm	Chronic exposure linked to liver damage and potential carcinogenicity
Apples	Chlorpyrifos	0.2 ppm	Banned in 2020	Neurodevelopmental effects in children; acute toxicity at higher doses
Rice	Atrazine	0.1 ppm	0.1 ppm	Endocrine disruption, impact on reproductive health
Tomatoes	Deltamethrin	0.05 ppm	0.1 ppm	Acute toxicity with neurological effects, especially in young children

(SPS) measures, and compliance with these regulations is essential for maintaining uninterrupted trade [64]. For instance, many countries have established stringent regulations concerning pesticide residue levels in rice, and incidents of chemical contamination have resulted in rejected shipments (Table 3). A notable example is the rejection of basmati rice exported from the Indian states of Punjab and Haryana due to exceeding pesticide residue limits [65]. Similarly, the European Union (EU) has halted imports of aromatic basmati rice because tricyclazole residues surpassed the maximum allowable MRL [66]. It is important to note that regulatory frameworks and lists of banned pesticides vary significantly across countries. These differences can complicate trade, as exporters must ensure compliance with each importing country's unique standards. This disparity can lead to trade barriers, particularly when pesticides allowed in one country are prohibited in another, resulting in rejected shipments and economic losses.

Evaluating EU food safety standards and twenty-first century trade barriers: implications for Indian exports and agricultural policies

Vineyard farmers in Maharashtra are facing significant challenges after the European Union (EU) rejected a shipment of table grapes due to trace amounts of chlormequat chloride, a plant growth regulator [67]. The EU has set a maximum residue limit (MRL) for food at 1% (0.01 mg/kg). In 2019, the EU conducted a control program that analyzed 12,579 samples from 12 commonly consumed food products for the presence of 182 pesticide residues. The results revealed that 53% of the samples had residues below the limit of quantification (LOQ), while 45% had residues above LOQ but within MRL limits (Table 2). However, 2% of the samples exceeded the MRL, and 1% were classified as non-compliant [68]. Data from EUROPHYT, covering the period from 2005 to 2017, indicate that Indian export commodities faced more border rejections than those from Brazil. Although China received more notifications, India recorded a higher export volume (Table 3). During this period, 1324 Indian consignments were intercepted, compared to 922 from Vietnam, 602 from China, 452 from Brazil, and 114 from Turkey. According to the FAO report, the United States rejected 1698 products from India. Other countries, including Vietnam, Saudi Arabia, Japan, and Bhutan, have also rejected Indian exports such as mangoes, okra, chilies, table grapes, tamarind, peanuts, curry leaves, prawns, and shrimps due to high levels of chemical residues. The highest number of interceptions occurred in 2012 and 2013, particularly affecting exports of mangoes, bitter gourd, eggplant, snake gourd, and taro, resulting in bans on several Indian export products [69]. Agricultural economists and policymakers recognize that in the twenty-first century, trade barriers, particularly those related to Sanitary and Phytosanitary (SPS) regulations, represent a critical component of Non-Tariff Measures (NTMs). These measures are less transparent but have a greater potential to disrupt trade than traditional tariff-based protections [70]. SPS regulations significantly affect the trade of agricultural and food commodities, influencing market access both positively and negatively [71].

Table 3 Pesticide-related product interceptions by the EU and US

Country	Number of interceptions (2019)	Common reason for interception	Impact on trade relations
India	120	Exceeding MRLs for chlorpyrifos, DDT	Temporary bans on mango and rice exports
Vietnam	85	Banned pesticides (e.g., carbendazim)	Delayed shipments of agricultural products
Brazil	60	Use of unapproved pesticides on soybeans	Increased scrutiny on agricultural imports
China	95	Mislabeling of pesticide content on tea leaves	Reduced market share in the EU and US

Assessing the factors affecting pesticide residue levels and their environmental consequences

Insecticides are frequently applied to cereal grains before storage to protect them from pests. However, residues of deltamethrin and cypermethrin in pulses persist even after processing methods such as cooking or washing, suggesting that these pesticides may have penetrated deep into the grains. This implies that the seed coats of pulses may contain the highest concentrations of cypermethrin [72]. As a result, removing these pesticides from grains is particularly challenging due to their potential infiltration into the seeds [73]. The environmental impact of pesticide use has become a growing concern within the scientific community. Pesticides are primarily used to control and reduce pest organisms that threaten agricultural crops and livestock [74]. While they are critical tools in agriculture, significantly contributing to productivity and food security, the widespread and indiscriminate use of pesticides has led to numerous adverse effects on human health, microorganisms, wildlife, and ecosystems [75]. The overreliance on pesticides has broad consequences, impacting not only target pests but also other biological systems. Human health is compromised due to exposure to pesticide residues, and the delicate balance of microbial communities in soil and aquatic ecosystems is disrupted [76]. Both domesticated and wild animals experience indirect consequences, such as habitat and food chain disturbances. Furthermore, pesticide pollution degrades soil quality, contaminates water sources, and harms non-target species, significantly impacting the environment [77]. Thus, the indiscriminate and excessive use of pesticides has resulted in numerous negative effects on human health, microorganisms, animals, and the environment, as outlined below.

Health risks of pesticide residues: bioaccumulation, food chain impacts, and global health consequences

Impact on human health

Pesticide residues enter the environment and bioaccumulate in various sources, eventually moving through the food chain and posing significant health risks [18]. The indiscriminate use of pesticides has led to severe health issues, with children being particularly vulnerable [78, 79]. Even low levels of pesticide residues found in food have become a global concern, as many persistent chemicals, such as persistent organic pollutants (POPs), accumulate throughout the food chain, negatively impacting human health and social welfare. One-third of the world's pesticide poisoning cases are reported in India. Higher levels of pesticide residue consumption have been linked to diseases such as cancer, blindness, liver disorders, and neurological illnesses [75] (Table 4). Data following the Green Revolution revealed that nearly 800,000 people have died due to chemical pesticide contamination [80]. Additionally, approximately 20,000 people die annually from pesticide-contaminated food in several developing countries [81].

Currently, no genotoxic pesticides are approved for use in food products intended for international trade. However, organophosphates and carbamates, commonly used pesticides, can disrupt the nervous system by interfering with nerve signal transmission. Prolonged exposure to pyrethroids, including deltamethrin, resmethrin, cypermethrin, and fenvalerate, has been associated with genetic damage and reproductive issues [82]. Pesticide poisoning has become a significant global health concern, primarily linked to agricultural practices and other chemical-intensive activities that put users at risk. The severity of pesticide-related health risks varies by region and the specific occupations of farmers, leading to both chronic and acute health disorders [83, 84] (Table 5). According to the World Health Organization [2], West African countries, particularly Nigeria, experience higher levels of occupational pesticide exposure compared to other regions. This elevated risk is largely due to insufficient protective measures, such as the use of faulty application tools, inadequate disposal facilities, limited practical training, and unsafe storage practices. Moreover, even individuals living in areas where pesticide use is uncommon may still be exposed to low levels of pesticide residues through contaminated water, air, and food [85].

Molecular mechanisms of pesticide-induced cellular and subcellular disruption

The impact of pesticides on cellular and subcellular processes is complex and involves multiple molecular

Table 4 Pesticides and their associated health hazards as adapted from the recent review by Tudi et al. [75]

Pesticide	Health hazard	Acute versus chronic exposure	Documented incidents
Paraquat	Severe lung damage, fatality	Acute (inhalation/ingestion)	High mortality in paraquat poisoning cases in Southeast Asia
DDT	Endocrine disruption, cancer	Chronic (long-term exposure)	Bioaccumulation observed in Arctic wildlife populations
Glyphosate	Potential carcinogen, liver damage	Chronic (food exposure)	Studies linking glyphosate to cancer in farmworkers in the US
Malathion	Neurological effects, seizures	Acute (high-level exposure)	Reports of seizures in children after accidental exposure in Latin America

Table 5 The residential and occupational exposure of the pesticides leads to various physiological and neurological disorder in human beings recorded across the countries

Sl. No.	Country reported	Major symptoms observed
Organophosphates (OPs)		
1.	South Africa, USA	Anxiety, headache and dizziness
2.	India	Giddiness, headache, ocular symptoms and paraesthesia
3.	Iowa and North Carolina, USA	Reduction of the motor speed and coordination along with verbal memory
4.	West Cape Province of SA	Anxiety, attention deficit or hyperactivity disorder (ADHD) and depression
5.	Italy	Distal numbness and lower limbs muscle pain, weakness and depression
6.	South-Eastern Spain; London	Affected neuropsychological functions viz., attention, expressive language, memory, motor performance, perception, reasoning skills
7.	Southern Brazil	Abdominal pain, anxiety and depression, headache, hypertension, dermatitis, diarrhea and hypersalivation
8.	Asia, Africa, America	Regular activity affective disorders
9.	Oregon, USA	Affected attention, remembrance and reaction time
10.	North-Eastern Colorado, USA	Dizziness, eye irritation, headache, nausea, skin irritation or vomiting
12.	Egypt	Neurological abnormalities
13.	Oregon and Columbia, USA	Poor learning and reaction
14.	North and South-West regions of England	Anxiety and depression
Organochlorine (OCs)		
15.	Finland	Autism spectrum disorders (ASD) and neuro-developmental disorders
16.	North Indian, Texas, USA	More risk of Alzheimer's disease (AD)
17.	Mexico Community	Impairment in circulatory, dermatological, digestive, renal, respiratory, reproductive and neurological, system
18.	USA	Decrease in mental developmental of the teen
Mixture of insecticide groups		
19.	Sri Lanka (OPs and carbamates)	Activity of the cholinesterase inhibited
20.	Kenya, East African (OPs and carbamates)	Eye and respiratory disorder, problem in central nervous system with inhibited cholinesterase
21.	N-E Colorado and Iowa and North Carolina, USA (OPs and others)	Depression because of poor health in long run due to financial crisis caused by pesticides exposure
22.	China (OPs and carbamates)	Anxiety, depression, increased anger

Data retrieved from Kori et al. [83] and Pathak et al. [84]

mechanisms. Pesticides disrupt cellular homeostasis and function through various pathways, leading to a broad spectrum of adverse effects [86]. Understanding these mechanisms is essential for comprehending the health risks associated with pesticide exposure [87]. Pesticides have various molecular targets in humans, which may lead to potential health effects. However, studies examining these health implications often yield inconclusive results, with some research indicating significant risks, while others find minimal or no effects at typical exposure levels. Many of the most detrimental health outcomes, such as neurological and endocrine disruptions, are linked to direct pesticide exposure, particularly among agricultural workers and farmers who handle pesticides regularly. Conversely, pesticide residues found in food are typically at much lower concentrations, regulated by safety limits, and pose a substantially lower risk to the general population. A schematic representation of the mechanisms by which pesticides impact cellular and subcellular functions is provided in Fig. 2 [88]. One major effect of pesticides is the induction of oxidative stress within cells by generating reactive oxygen species (ROS), which disrupts the balance between pro-oxidants and antioxidants [88]. This imbalance can damage cellular components such as lipids, proteins, and DNA, ultimately affecting cell viability and function. Many pesticides are also recognized as endocrine disruptors, interfering with hormonal functions in the body. Such disruptions impair cellular signaling, alter gene expression, and impact overall cellular activity [89].

Pesticides are linked to epigenetic modifications, including DNA methylation changes, histone modifications, and shifts in non-coding RNA expression [88]. These alterations can lead to mutations, chromosomal abnormalities, and may contribute to cancer initiation and progression [90]. Additionally, pesticides interfere with cellular signaling pathways that control cell growth, proliferation, and survival, with disruptions in

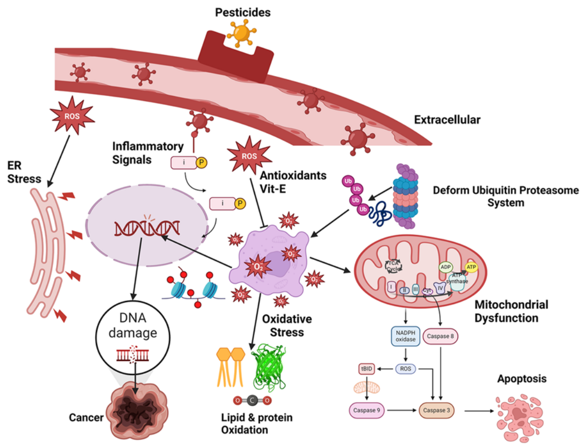


Fig. 2 Molecular mechanisms associated with pesticides induced carcinogenesis adapted and modified from Sabarwal et al. [88]. Figures created using BioRender software

these pathways potentially leading to abnormal cellular responses and disease development, including cancer [91]. Certain pesticides also impair mitochondrial function, which can reduce energy production, increase ROS generation, and trigger apoptotic pathways [92]. Furthermore, pesticides can modulate immune cell function, making individuals more susceptible to infections and diseases [88]. At the metabolic level, pesticides interfere with essential biochemical processes, leading to cellular dysfunction and damage. The broad effects of pesticides on cellular and subcellular activity encompass numerous mechanisms, including oxidative stress, endocrine disruption, epigenetic alterations, DNA damage, interference with cellular signaling pathways, mitochondrial dysfunction, immune modulation, and metabolic disruption [93]. Gaining a comprehensive understanding of these mechanisms is crucial for identifying the health risks associated with pesticide exposure and developing strategies to mitigate their impact on human health.

The impact of pesticide use on soil microflora and ecosystem

The frequent application of pesticides contributes significantly to biosphere contamination, adversely affecting non-target organisms, including beneficial microflora [94]. Rising levels of human-induced environmental pollution impact a broad range of flora and fauna, with substantial negative consequences for human health [95]. Within this context, the systematic use of pesticides has led to a decline in the average soil microflora in rice–wheat crop ecosystems [96, 97]. Notably, the application of oxytetracycline (a bactericide) and captan (a fungicide) has caused marked reductions in bacterial and fungal populations, respectively (Fig. 3). Additionally, herbicides have been shown to inhibit methanogenic bacterial populations in crop fields, with significant implications for microbial processes like nitrogen mineralization via ammonification and nitrification [98]. Glomalean arbuscular mycorrhizal fungi, essential for plant nutrient acquisition, are especially sensitive to fungicides [99].

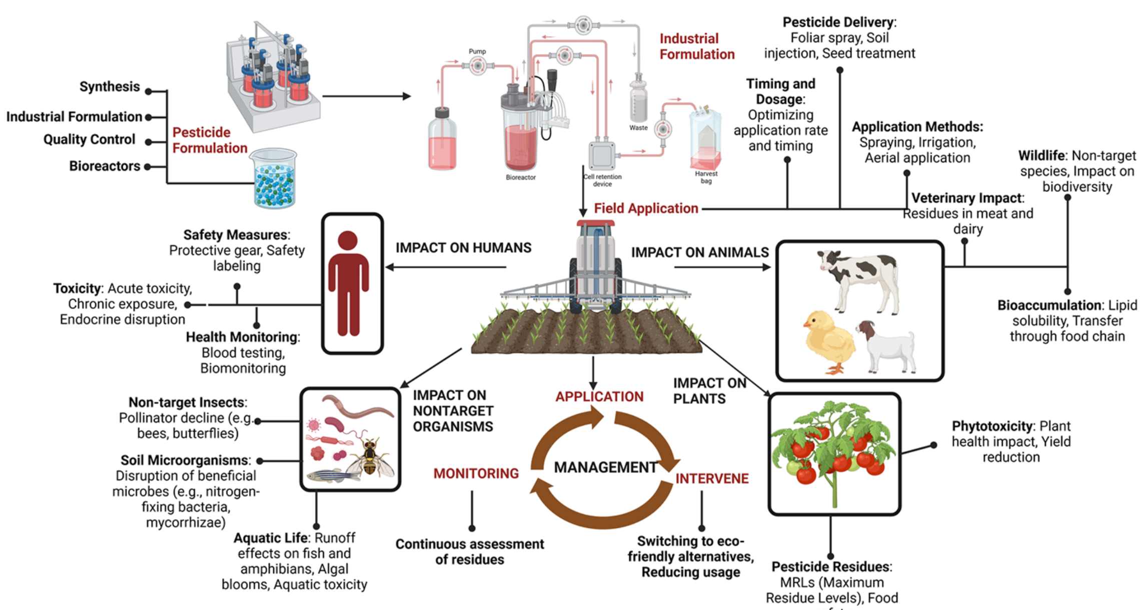


Fig. 3 Thematic diagram of the synthesis, production, uses, effects and eco-friendly management of pesticide adapted and modified from Pathak et al. [84]. Figures created using BioRender software

Herbicide applications have also been shown to reduce arbuscular mycorrhizal fungi populations, which may contribute to an overall decline in soil health [100]. In soils contaminated with DDT, there has been a decrease in soil algae and cyanobacteria diversity, alongside the rise of resistant green algae, illustrating the detrimental effects of pesticide contamination on soil microbial communities and ecosystem health. These microorganisms serve as bioindicators in the environment, reflecting the presence of xenobiotic or pesticide compounds in soils through reduced spore loads and population declines [101]. Elevated concentrations of herbicides have been observed to reduce total chlorophyll, total sugars, and dry biomass in plants [102]. Even at lower concentrations, pesticides can disrupt the electron transport chain, affecting photosynthesis and altering plant morphology. Specific pesticides, including endosulfan, atrazine, and chlorothalonil, have been found to decrease the diversity of protist taxa [103], while chemicals such as dimethoate, fenpropimorph, and pirimicarb influence protozoa colonization in soil ecosystems [104].

The long-term impact of pesticide residues on non-target organisms in the food chain

Chemical toxicity depending on a compound's function and the extent of exposure, which can occur through ingestion, inhalation, or direct skin contact [105]. Numerous reports indicate that pesticide residues in animal products often go undetected; however, these residues can enter the human food chain through dietary pathways [106]. Studies have documented significant population declines in various animals, including amphibians, bees, fish, birds, and small mammals, due to environmental dispersion of pesticide residues [47, 107]. Thus, improving quality control for animal products is essential, as contaminated feed and fodder consumed by animals can propagate pesticide residues through different levels of the food chain [47]. While herbicides are applied to control weeds, their residues may persist for weeks to months, impacting insect survival and egg-laying by altering host plant availability [108]. Additionally, herbicide application reduces natural flora and fauna by limiting the availability of host plants, which provide shelter, nesting sites, sources of nectar and pollen, and overwintering habitats for many non-target insects [109, 110]. This decline in host plants correlates with a significant reduction in the abundance of non-target organisms such as crickets, mites, ground beetles, and spiders in corn fields following the application of 2,4-D and glyphosate [111]. Furthermore, herbicides like DCBN (0.1%) have been shown to reduce the parasitization rate in *Aphidius rhopalosiphi* [112], and the population of the lacewing *Mallada signatus* has declined after feeding on *Helicoverpa armigera* exposed to insecticides [113]. While these pesticides effectively target specific pests, their residues can cause long-term harm to non-target species.

Navigating pesticide regulation and food safety, challenges and responsibilities in India and beyond

Pesticides have become essential in modern agriculture, boosting productivity and contributing to food security. However, their widespread use since the Green Revolution has raised concerns over pesticide residues in food [114]. Ensuring food safety is a shared responsibility involving all stakeholders along the food supply chain, from farmers to consumers [115]. Governments play a central role by setting standards and enforcing regulations, while trade organizations, consumer groups, professional bodies, and academic institutions contribute to policy development. Consumers, too, bear the responsibility of understanding food safety standards and handling food products appropriately [116]. India's food safety system is complex and multi-layered, presenting challenges for government oversight. The Central Insecticides Board and Registration Committee (CIBRC) and the Food Safety and Standards Authority of India (FSSAI) are the primary bodies regulating pesticide use in the country. The CIBRC provides guidance on pesticide manufacturing, usage, and safety, overseeing registration after evaluating efficacy and safety data submitted by manufacturers [117]. Meanwhile, FSSAI, operating under the Ministry of Health and established by the Food Safety and Standards Act of 2006, acts as the primary regulatory authority for food safety [118]. Additional organizations, such as State Agricultural Universities (SAUs) and State Departments of Agriculture (SDAs), provide guidelines on pesticide application in agriculture [119]. In 2003, the Joint Parliamentary Committee (JPC) highlighted pesticide contamination in carbonated beverages, and the Center for Science and Environment subsequently advocated for setting standards for water-based products, including fruit juices and soft drinks [120]. Key regulations enacted by the Indian government include the Insecticides Act of 1968, the Food Safety and Standards Act of 2006, and the Pesticide Management Bill of 2020, aimed at overseeing pesticide use with regard to environmental impact, food safety, and public health [121]. Globally, frameworks like those in the European Union (EU) prohibit the sale of food products with contaminants that exceed permissible levels. The EU has set maximum limits for various harmful substances, such as aflatoxins, heavy metals, dioxins, and nitrates, due to their toxicity risks in the food supply [122]. The EU enforces food and feed laws through rigorous inspections to ensure compliance, while the European Food Safety Authority (EFSA) plays a vital role in environmental risk assessment, setting specific targets to minimize pesticide impacts on soil biodiversity, food production, and climate resilience [123, 124]. In the United States, four primary agencies regulate food safety: The Food and Drug Administration (FDA) under the Department of Health and Human Services (DHHS), the Food Safety and Inspection Service (FSIS) of the USDA, the National Marine Fisheries Service (NMFS) within the Department of Commerce, and the Environmental Protection Agency (EPA). These agencies coordinate through over 50 interagency agreements to streamline regulatory efforts [125]. Together, these authorities are essential in managing pesticide impacts on the environment, safeguarding food safety, and preventing contamination of food products that reach consumers.

Pesticide residues in food, detection, natural degradation, and remediation strategies

The role of chromatography and mass spectrometry

Human nutritional needs, particularly those derived from food, are fundamental and often prioritized above other necessities such as clothing and shelter. However, pesticide use in agriculture raises substantial concerns, as these chemicals frequently leave residues that pose risks to public health and the environment [126]. The assessment of these risks has been significantly enhanced by the use of advanced analytical techniques, notably chromatography coupled with mass spectrometry [127]. In agricultural contexts, pesticide residues have become a pressing issue due to their potential harmful effects. Chromatography and mass spectrometry have thus emerged as crucial tools for evaluating and quantifying these residues [128]. This analytical approach enables the accurate identification and measurement of pesticide residues in a wide range of samples, including agricultural products and environmental matrices [23]. The significance of chromatography and mass spectrometry lies in their ability to provide precise and dependable data on the presence and levels of pesticide residues, which is essential for ensuring the safety of food intended for human consumption. These methods are extensively used within the scientific community to conduct comprehensive analyses, helping to ensure that the food supply meets stringent safety standards [129].

Mechanisms of biodegradation and remediation

Pesticides present in soil and the environment can undergo various transformations that result in the formation of non-toxic compounds through a process called biodegradation. This transformation is facilitated by microorganisms that partially or completely break down these compounds [130]. After harvest, cereal grains are often treated with pesticides to reduce losses during bulk storage. Residues tend to accumulate more in the bran than in other parts of the seed, as lipophilic pesticides concentrate in areas with higher triglyceride levels, such as the germ and bran [131, 132].

In fruit juice, pesticide residue concentrations depend on how the pesticide partitions between the juice and the fruit skins. Lipophilic residues generally remain in the skin and do not transfer significantly to the juice. For fruits and vegetables, residues are often more concentrated near the stem and the outer layers (receptacle and exocarp) than in the flesh (sarcocarp or pericarp). Similarly, in leafy vegetables, pesticide residues are more abundant in the upper layers than in the lower ones [133]. Studies indicate that the outer layers of cereal grains absorb the majority of pesticide residues, suggesting that processing methods such as milling and grinding can help reduce these residues in food. Due to the penetrative nature of many pesticides, their removal through cooking or washing is often challenging. The persistence of residues depending on the physicochemical properties of both the food and the pesticide, with most compounds tending to adsorb to surfaces [134]. Techniques such as washing, peeling, and treating with agents like ethanol, turmeric, sodium bicarbonate, vinegar, and table salt can significantly reduce residue levels [134]. In dairy products, pesticide contamination is primarily associated with fat, resulting from contaminated feed and fodder [135]. Consequently, residue levels are often higher in products like butter, cheese, ghee, and malai compared to raw milk [136]. In meat, pesticides mainly accumulate in fatty tissues and egg yolk, which contain more lipid-soluble pesticides than albumin [134]. Research has shown that various microorganisms—including bacteria, fungi, actinomycetes, and algae—can effectively degrade pesticides and organic waste [137–139] (Table 6). For example, species such as *Micromonospora chalcea*, *Nocardia amarae*, *Nocardia farcinia*, *N. vaccini*, *Streptomyces alanosinicus*, *Streptoverticillium album*, and *S. atratus* from Sangli District, Maharashtra, have been identified for their ability to degrade carbofuran [140]. Additionally, white-rot fungi and the green microalga *Chlamydomonas mexicana* have been found to degrade atrazine [141, 142]. Algal and cyanobacterial species like *Chlorella*, *Scenedesmus* sp., *Chlamydomonas* sp., *Stichococcus* sp., Nostoc muscorum, and *Anabaena* sp. can also degrade the toxic organophosphate compound fenamiphos in soil [143]. The use of biosurfactants in pesticide-contaminated sites enhances the bioavailability of pesticides, accelerating bioremediation. Biosurfactants lower surface and interfacial tensions of immiscible fluids, improving the solubility and

Table 6 List of major groups of pesticide degrading microbes

Sl. No.	Microbe group	Species	Degrading pesticide class	References
1	Actinomycetes	Actinomyces, *Micromonospora, Nocardia, Streptomyces*	Organochlorine, organophosphate, atrazine, pyrethroids	Huang et al. [137]
2	Algae	Small green algae Chlamydomonas Genus of diatoms		
3	Bacteria	*Pseudomonas*	Organochlorine, organophosphate	
		Bacillus	Organochlorine, organophosphate glyphosate, polycyclic aromatic hydrocarbons	Upadhyay and Dutt, [138]
		Flavobacterium; Alcaligenes		
4	Fungus	*Aspergillus* sp., *Aspergillus fumigatus*, *Cladosporium, Fusarium, Rhizopus, Penicillium, Mortierella* sp. *Mucor, Trichoderma* spp, white-rot fungi	Alachlor, atrazine, 2,4-D, carbamate pyrethroid, fipronil, organochlorine	Wolfand et al. [139]

adsorption of hydrophobic pesticide contaminants [94]. Their biodegradability, low toxicity, high selectivity, and broad action spectrum across varying pH, temperature, and salinity conditions, along with a low critical micelle concentration (CMC), make them highly effective for pesticide remediation efforts [144]. Figure 4 presents a schematic illustration of in vitro screening of biosurfactant-producing microbes and their remediation mechanisms for soil pesticides.

Alternative methods for the elimination of pesticide residues in agricultural products

In addition to natural and biological conversion processes, various alternative methods are available to remove pesticides from food components [144, 145].

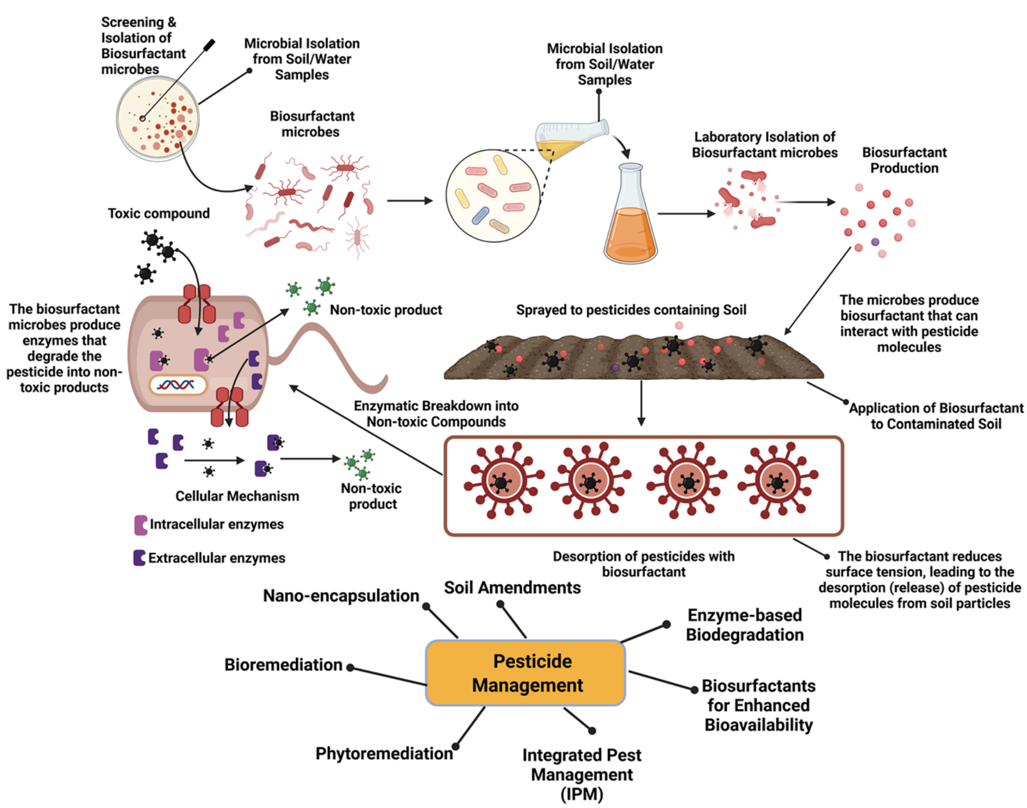


Fig. 4 Laboratory isolation of microbial bio-surfactant and their remediation mechanism against the soil pesticides as adapted and modified Raj et al. [94]. Figures created using BioRender software

These techniques include scrubbing firm fruits and vegetables, rinsing with water, soaking in solutions like vinegar, salt, or lemon, as well as blanching, peeling, and discarding the outer layers of leafy greens. Other methods such as canning, juicing, baking, pasteurization, and wiping dry produce with a clean cloth or paper towel can also help eliminate pesticide residues [146]. Boiling animal and dairy products has been effective in significantly reducing pesticide residues, while techniques like concentration and dehydration further contribute to lowering residue levels in food materials [146]. However, it is important to note that certain processes may inadvertently increase residue levels due to factors such as lipid affinity and concentration effects [147]. Nevertheless, employing a combination of these strategies offers a comprehensive approach to minimizing pesticide residues in food, promoting safer and healthier consumption of agricultural products.

Challenges in monitoring pesticide residues: regulatory perspectives and health risks

Several health issues have been associated with consuming plant-based foods containing pesticide residues that exceed maximum residue limits (MRLs), especially when considering both daily intake and acute reference dose (ARD) standards. Consumers are generally considered at low risk if their anticipated food intake remains within ARD limits. Effective monitoring of pesticide residues and establishing permissible limits across various food commodities are essential to ensure human safety [63]. For instance, the European Food Safety Authority (EFSA) has set the MRL for glyphosate in lentils at the highest level of analytical quantification, irrespective of toxicity levels. In 2011, glyphosate residues exceeding MRLs were reported as posing no public health risk [123]. Nonetheless, addressing agricultural practices directly would likely have been a more effective solution than simply raising the MRL. The legal framework governing pesticide residues is intricate, involving both national and international regulations and standards. The primary goal is to ensure the safe, responsible use of pesticides in agriculture while minimizing risks to human health, the environment, and food safety. Each country has its regulatory authorities, and international agreements are instrumental in addressing the challenges posed by pesticide residues. The Codex Alimentarius Commission (CAC), established by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), sets international food safety standards, while the Codex Committee on Pesticide Residues (CCPR) determines MRLs for pesticides in food. The Rotterdam Convention regulates the trade and use of specific hazardous pesticides and chemicals, supporting informed decision-making regarding their import and export through information exchange. However, effectively monitoring pesticide residues remains a significant challenge [63], particularly as many countries lack sufficient resources for regular and comprehensive testing. The introduction of new pesticides and modifications in formulations further complicates risk assessment and the establishment of regulatory frameworks [23]. Access to reliable data on pesticide usage, residues, and their impacts is crucial, yet transparency in reporting and data sharing remains limited in many regions. Strengthening international cooperation and information exchange is essential to address these challenges and harmonize standards in global trade.

Conclusion and recommendations

Chemical pesticides play a vital role in sustaining agricultural productivity and ensuring global food security by effectively controlling pest infestations in crops and storage. Despite the growing awareness of alternative pest control methods, a full transition away from chemical pesticides is likely to be gradual, given their widespread usage worldwide. However, the persistent reliance on pesticides presents significant challenges. Inadequate safety practices, such as limited comprehension of safety labels among farmers and the lack of proper protective equipment, exacerbate health and environmental risks. The adverse effects of pesticide use are extensive, impacting human health-both physiologically and neurologically—as well as harming non-target organisms, soil health, groundwater, and even local climate patterns. Recognizing the necessity of pesticides in agriculture, akin to the role of medicine in managing illness, emphasizes the importance of responsible usage practices. Targeted application to effectively manage pests while safeguarding food crops is essential. Routine monitoring of pesticide residues before export and consumption is critical to reduce risks, such as the rejection of contaminated consignments in international trade.

Recommendations and future perspectives

This review provides comprehensive insights into the challenges and management strategies surrounding pesticide use, contributing novel perspectives on sustainable approaches to pesticide residue mitigation. Based on the findings, we recommend the following actions:

Enhanced education and training: Improving awareness among farmers and agricultural workers about safe pesticide handling, including the proper use of protective gear and an understanding of safety labels, is essential. Government bodies, agricultural extension services, and NGOs can collaboratively develop training programs that address these critical knowledge gaps.

Adoption of integrated pest management (IPM): A robust shift towards IPM practices, combining biological controls, crop rotation, habitat management, and reduced pesticide application, offers a sustainable alternative to traditional chemical reliance. Expanding IPM adoption through policy incentives can significantly reduce the environmental and health impacts of pesticides.

Development of advanced remediation techniques: Future research should focus on developing and optimizing food processing techniques, soil amendments, and biosurfactant-based remediation methods to effectively remove pesticide residues from food products and soil. Research into novel, eco-friendly pesticide alternatives should also be prioritized to provide safer options for pest management.

Strengthened regulatory frameworks and monitoring systems: Establishing stricter regulatory standards for pesticide residues, especially in emerging markets, is crucial for consumer safety. Implementing routine monitoring and setting stringent MRLs (maximum residue limits) can minimize exposure risks and prevent non-compliance in global trade. International collaboration to harmonize these standards would further enhance trade safety.

Promotion of research and innovation in alternatives: Supporting innovation in non-chemical pest management solutions, such as biopesticides and genetic pest resistance, can reduce dependency on traditional pesticides. Incentivizing research in these areas can pave the way for more sustainable agricultural practices.

The insights and recommendations presented in this review emphasize the critical need for a multifaceted approach to pesticide residue management. By implementing these strategies, agriculture can progress towards a more sustainable model, balancing productivity with environmental stewardship and public health protection. This review aims to encourage policymakers, researchers, and practitioners to adopt holistic strategies that will lead to a safer and more sustainable agricultural future.

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No datasets were generated or analysed during the current study.

Declarations

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This manuscript is an original review paper and has not been published in other journals. The authors agreed to keep the copyright rule.

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