PESTICIDE EXPOSURE AND HUMAN HEALTH RISKS IN VEGETABLE PRODUCTION: A NARRATIVE REVIEW OF RESIDUES, OCCUPATIONAL HAZARDS AND RISK-REDUCTION STRATEGIES

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Highlights

- Overuse of pesticides in vegetable cultivation poses serious health concerns to farmers, including neurological and reproductive diseases.
- Despite India's low per-hectare pesticide use, hazardous handling and poor MRL compliance led to widespread food poisoning.
- Long-term exposure may have psychological, neurological, reproductive, and carcinogenic effects.
- Solutions include implementing sustainable methods, enforcing rules, and empowering farming communities with focused training and health monitoring.

ABSTRACT

In vegetable farming, synthetic pesticides are commonly used, which has greatly increased yields provided an opportunity to manage pests. The disadvantage is that the use of synthetic pesticides comes with very high risks to our long-term health and food safety, particularly for rural communities. In this review paper, we explore the Indian context in terms of the usual mechanisms of pesticide contamination, levels of pesticide residues in commonly consumed vegetables, and the resulting long-term health impacts. While India is actually using fewer pesticides per acre than the world average, unsafe practices in handling them, harvesting at immature stages, and a lack of regulatory and enforcement capabilities have led to residues that exceed legally allowable limits. Vegetables such as tomatoes, brinjal and chilli commonly have pesticide residues that resist washing and persist during storage, and enter the human food chain, based on numerous studies. Prolonged work exposure to chemically contaminated agricultural produce has led to various health concerns (including neurological conditions such as Alzheimer's and Parkinson's, cognitive decline, reproductive issues, endocrine disorders, liver conditions, respiratory conditions, and increased cancer risks). Extremely contaminated agricultural areas have also been connected to various mental health issues, such as anxiety, depression, and sleep issues. The evaluation points out the urgent need for standardization and ongoing monitoring, as well as gaps in enforcing Maximum Residue Limits (MRLs). It supports using personal protective equipment, monitoring residues, training farmers, applying integrated pest management (IPM), and educating consumers as key strategies. Promoting sustainable farming practices and shifting towards biopesticides are essential steps to protect environmental sustainability, food security, and public health.

KEYWORDS: Pesticide, Human health, Risk, Pesticide contamination, Residue level.

INTRODUCTION

Modern agriculture significantly relies on pesticides to manage pest threats, improve crop yields, and ensure food security. As the global population is projected to reach 10 billion by 2050, increasing agricultural productivity is crucial to meet the growing food demand. Tudi *et al.* (2021) emphasized that pesticides are critical for reducing crop losses and improving yields, ensuring stable and abundant food supplies to feed this expanding population. Moreover, with the increasing unpredictability of weather patterns due to climate change, the incidence of pest outbreaks is likely to grow, further necessitating the use of pesticides to safeguard crops and support global food security. Globally, pesticide consumption is expected to increase from 4.3 million metric tons in 2023 to 4.41 million metric tons by 2027, as shown in Figure 1 (Source: Statista ,2023).

According to Statista (2023), the Americas lead global pesticide use (51.1%), followed by Asia (28.6%) and Europe (12.8%), while Africa and Oceania together contribute under 8%. Transport Corporation of India Ltd (2023) states that the production and export of pesticides are also heavily concentrated in a few regions. China emerged as the largest exporter of agricultural pesticides in 2022, with an export value of approximately $11 billion, followed by India, the United States, and France, each contributing between $4 billion and $5 billion. China is both the largest producer and the largest user of pesticides in the agricultural sector globally (Sharma *et al.*, 2019). Meanwhile, the demand for vegetables, both domestically and internationally, has surged due to shifting dietary preferences toward healthier, low-carb diets. According to ITC Trade Map (2023), global vegetable exports were valued at $84.9 billion, with China, Mexico, the Netherlands, and Spain ranking as the leading exporters. India, with a vegetable export value of $2.1 billion in 2023, was a significant player, exporting major crops like onions, tomatoes, and cauliflower to countries such as Bangladesh, the UAE, Malaysia, and the U.S. However, the high reliance on pesticides in vegetable farming to meet the growing demand is a matter of concern due to the resulting health risks.

1. METHODOLOGY

This review draws upon peer-reviewed research articles accessed through ScienceDirect, Scopus, Google Scholar, PubMed, and ResearchGate. Keywords used include: “pesticides”; “pesticide usage”; “health risk”; "pesticide contamination"; "residue levels"; "chronic health effects" and "vegetable farming”. Studies were selected based on their relevance to pesticide impacts on human health. Emphasis was placed on data from India and developing countries, and comparative figures from international studies were included for context.

2. RESULTS AND DISCUSSIONS

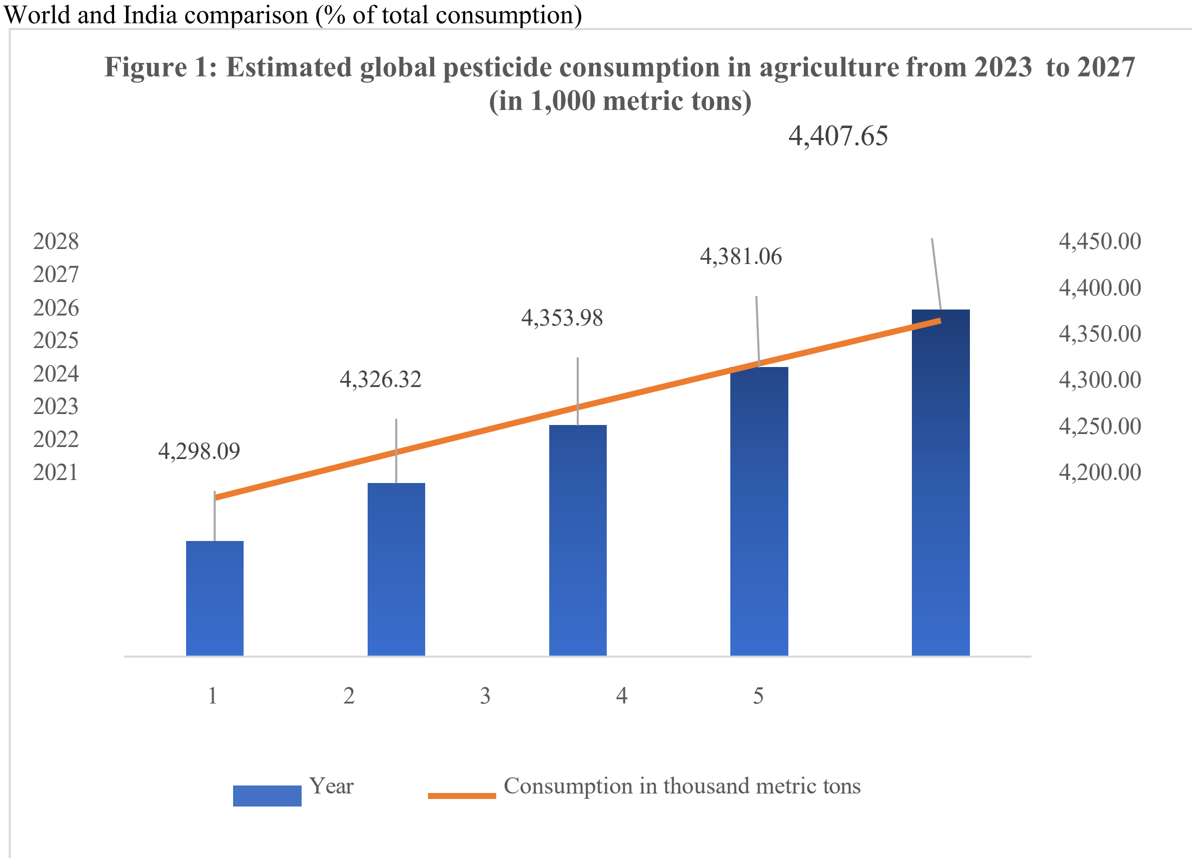
1. Pesticide Usage Pattern

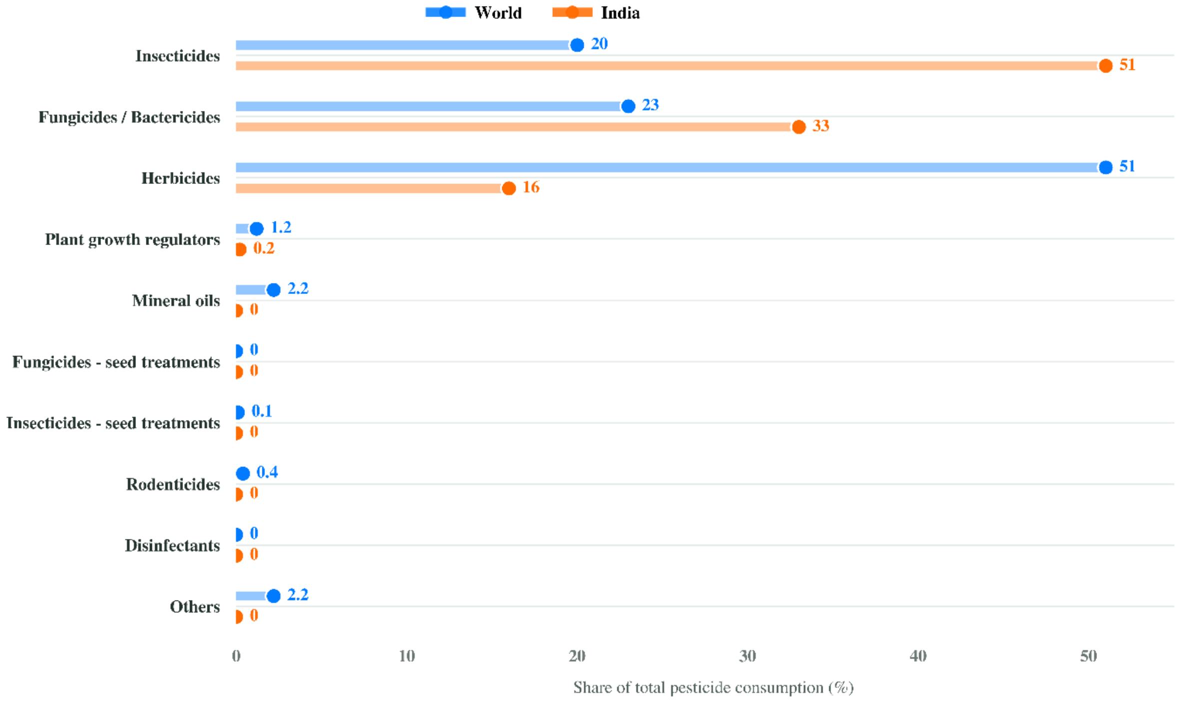
1.1. Indian context

India’s pesticide usage patterns diverge significantly from global trends. While herbicides dominate global pesticide consumption, insecticides account for 51.4% of India’s pesticide use, followed by fungicides (32.6%) and herbicides (15.8%). This is largely due to the country's focus on pest management in vegetable crops like okra, onion, and chili, which are vulnerable to insect damage. Furthermore, India's pesticide usage per hectare, at 0.4 kg, remains significantly lower than that of countries like China (1.83 kg/ha) and Brazil (10.9 kg/ha), highlighting a disparity in pesticide intensity despite the scale of agriculture in these countries (Figure 2).

Figure 2 – Various types of pesticide consumption in the world and India (2020)

World and India comparison (% of total consumption)





According to Janaki Rani *et al*. (2025), Uttar Pradesh, Maharashtra, Andhra Pradesh, and Punjab are among the states with the highest pesticide consumption in India, driven by extensive vegetable farming. Although India ranks 12th globally in pesticide consumption, its low per-hectare usage suggests a need for enhanced pesticide management strategies to mitigate the potential environmental and health impacts (Reddy *et al.,* 2024).

1.2. Pesticide Use in Tamil Nadu

As Janaki Rani *et al*. (2025) point out, crops such as brinjal and cauliflower, which are commonly grown in the region, demand frequent applications of insecticides and fungicides. While these chemicals help manage pests and ensure yield, they also introduce a set of growing concerns, particularly regarding pesticide residues and their impact on the health of those who handle them daily (El-Sheikh *et al.,*2022). Alarmingly, despite Tamil Nadu's prominence in agricultural output, there remains a notable absence of in-depth studies examining the state's pesticide usage trends and the chronic health outcomes experienced by its farming communities. The issue is not just about what chemicals are used, but how they are applied (Adanu.K.K.*et al.,*2022). (Mengistie *et al.,* 2015) revealed that many farmers in the region often engage in high- risk practices, such as reusing leftover pesticide solutions, spraying without proper protective gear, and failing to follow recommended safety intervals. Similar observations were made by Sathish *et al*. (2025), who reported that the routine neglect of safety measures continues to expose farmers to unnecessary risks during pesticide handling. These unsafe practices, as documented by Narmadha *et al.* (2025), are frequently driven by a lack of awareness, poor training, and limited access to protective equipment, especially among small and marginal farmers. Adding to the urgency, Kavitha and Suresh Kumar (2016) drew attention to the rise in pesticide-related health problems among farmers, attributing much of it to long-term, low-level exposure that accumulates silently over time. Earlier, (Pawestri & Sulistyaningsih, 2021) had already established a worrying link between chronic pesticide exposure and reproductive and neurological disorders among agricultural workers, suggesting that the problem has persisted for decades. The health risks are compounded by the fact that vegetables cultivated in the state frequently test positive for residues that exceed permissible limits. This not only threatens consumer safety but also underscores a critical need for stronger regulatory oversight (Reddy A.A *et al.,*2024). The way forward must involve both top-down policy reforms and bottom-up educational outreach, ensuring safer application practices, wider use of personal protection, and a shift toward more sustainable pest control methods.

2. Pesticide Residues in Vegetables

Over the past decade, the conversation around food safety has shifted dramatically, with pesticide residues in vegetables becoming one of the most pressing concerns. Take, for instance, everyday staples like cauliflower, brinjal (Rajasekar *et al.,* 2024), and chili crops that are heavily treated with pesticides due to their high susceptibility to pests. While these interventions are often necessary to protect crop yields, they come at a hidden cost. Bontha *et al.* (2024) observed that such vegetables frequently carry traces of chemical residues, raising red flags about their long-term impact on public health. This issue isn't new. More than a decade ago, (Boonkhao *et al.,* 2023), (EFSA,2019) cautioned against both acute and chronic health hazards resulting from dietary exposure to pesticide-laden foods. The risks, he argued, are not limited to isolated cases of poisoning; rather, they manifest slowly and silently, especially when regulatory safeguards are weak. In many regions, particularly where compliance with safe-use protocols is inconsistent, the problem is compounded by the misuse or overuse of pesticides. El-Sheikh *et al.* (2020) stated that Farmers, often unaware of the dangers, may apply higher than recommended doses or turn to banned chemicals in search of quick results. In India, regulatory frameworks are in place at least on paper. The Food Safety and Standards Authority of India (FSSAI) has established specific Maximum Residue Limits (MRLs) for a wide range of pesticides. However, as Viancelli *et al.* (2024) reported, the enforcement of these standards remains patchy. Cases of vegetables exceeding permissible residue levels are not uncommon, especially in states where monitoring mechanisms are under-resourced. Interestingly, a potential solution is now being explored. As Bhandari *et al.* (2020) noted, the government is considering a crop grouping system for MRLs a strategy that could simplify residue monitoring and help ensure better protection for consumers nationwide.

2.1. Pesticide Residue Level

Field residue studies (Malhat *et al.,* 2016) indicate that pesticide residues persist on crops for several days following application, gradually degrading over time depending on the chemical nature and environmental conditions. In India, the FSSAI has established MRLs for various pesticides across different vegetable crops (see Table 1). Established under the Food Safety and Standards Act of 2006, the FSSAI is tasked with creating science-based standards for food and regulating aspects such as manufacture, storage, distribution, and sale to ensure the availability of safe food for consumption. However, a significant number of pesticide-crop combinations lack established MRLs in India. To address this, the Government of India plans to introduce crop groupings, allowing for a single MRL to apply to a category of vegetables, simplifying the risk assessment process for numerous crops. The scientific panel on pesticide residues of the FSSAI bases its MRL recommendations on risk assessments that consider dietary consumption patterns, health implications, and the adoption of MRLs by the Codex Alimentarius Commission.

Table 1: MRLs for various pesticides across different vegetable crops

Crops	**Name of the Pesticide**	**MRL (mg/kg)**
Chilies	Acetamiprid	0.01
	Alpha naphthyl acetic acid	0.2
	Azoxystrobin	1.0
	Buprofezin	0.01
	Carbaryl	5.0
	Carbendazim	0.5
	Carbosulfan	2.0
	Chlorantraniliprole	0.03
	Chlorfenapyr	0.05
	Cuprous Oxide	0.01
	Cyantranilipole	0.05
	Deltamethrin (Decamethrin)	0.05
	Diafenthiuron	0.05
	Dicofol	1.0
	Difenoconazole	0.01
	Dimethoate	0.5
	Mancozeb	1.0
	metiram as CS2	0.05
	Fenpropathrin	0.2
	Flubendiamide	0.02
	Hexythiazox	0.01
	Imidacloprid	0.3
	Indoxacarb	0.01
	Lambda cyhalothrin	0.01
	Lufenuron	0.05
	Propargite	2.0
	Pyraclostrobin	0.05
	Spinosad	0.01
	Spiromesifen	0.1
	Triazophos	0.2
Bhendi	Acetamiprid	0.1
	Beta Cyfluthrin	0.01
	Buprofezin	0.01
	Cypermehrin	0.2
	Cyermethrin	0.2
	Cypermethrin	0.2
	Chlorpyriphos	0.2
	Deltamethrin (Decamethrin)	0.05
	Dimethoate	2.0
	Emamectin Benzoate	0.05
	Endosulfan	2.0

	Fenazaquin	0.01
	Fenpropathrin	0.5
	Fenvalerate	2.0
	Fluchloralin	0.01
	Imidacloprid	2.0
	Lambda cyhalothrin	2.0
	Malathion	3.0
	Quinalphos	0.25
	Triazophos	0.03
	Thiamethoxam	0.5
Tomato	Alpha-naphthyl acetic acid	0.1
	Acetamiprid	0.2
	Azoxystrobin	1.0
	Chlorantraniliprole	0.03
	Chlorpyrifos	0.5
	Cyantranilipole	0.03
	Cyazofamid	0.01
	Cymoxanil	0.01
	Deltamethrin (Decamethrin)	0.05
	Difenoconazole	0.2
	Dimethyl dithio carbamates	3.0
	Metiram as CS2	5.0
	Ethephon	2.0
	Fenvalerate	0.01
	Flubendiamide	0.07
	Imidacloprid	1.0
	Indoxacarb	0.05
	Lambda cyhalothrin	0.1
	Permethrin	
	Pyraclostrobin	0.01
	Spiromesifen	0.3
	Thiamethoxam	0.1
Brinjal	Beta Cyfluthrin	0.01
	Carbendazim	0.5
	Chlorantraniliprole	0.03
	Chlorpyriphos	0.2
	Chlormequat chloride (CCC)	0.1
	Cypermehrin	O.2
	Dimethoate	2.0
	Deltamethrin (Decamethrin)	0.2
	Diafenthiuron	1.0
	Zineb as CS2	0.01
	Endosulphan	2.0
	Etoxazole	0.2
	Fenazaquin	0.01
	Fenpropathrin	0.2
	Fenvalerate	2.0
	Flubendiamide	0.1
	Fluchloralin	0.01
	Imidacloprid	0.01
	Lambda cyhalothrin	0.2
	Quinalphos	0.25
	Propargite	2.0
	Spiromesifen	0.5
	Thiamethoxam	0.3
Onion	Chlorpyriphos	0.01
	Fluchloralin	0.01
	Lambda cyhalothrin	0.01
	Propaquizafop	0.01
	Pyraclostrobin	0.05
	Quizalofop-ethyl	0.01

(Source – Dione *et al.,* 2023; Rajasekar *et al.,* 2024)

2.2. Contamination Pathways

(Kalyabina *et al.*, 2021) studied the transfer of pesticides in food crops and introduced a dynamic plant uptake model based on interconnected compartments to estimate potential health risks associated with pesticide residues.

2.2.1. Premature Pathways

Field investigations in Nigeria (Yami *et al.*,2025) revealed that many smallholder farmers routinely bypass the recommended pre-harvest interval (PHI), particularly when crops face pest threats or market pressure. A study involving over 1,500 tomato producers in Northern Nigeria found that, in more than 30% of cases, vegetables were harvested just 3–5 days post-application, well below the safety threshold, resulting in residue levels that exceeded WHO safety limits

2.2.2. Improper washing and storage

Dione *et al.* (2023) reported that tomatoes sold in local markets typically do not undergo any form of decontamination to reduce pesticide residues, placing the burden of residue removal entirely on consumers during home preparation. Experimental findings by Amqam *et al.* (2019) demonstrated that washing tomatoes can reduce residues of specific pesticides like chlorpyrifos. Tiryaki and Pola (2022) further noted that the effectiveness of washing methods varied by pesticide type, with non-toxic acidic rinses, ozonated water, and ultrasonic treatments proving more effective than standard tap water rinsing.

2.2.3. Improve quality control at market level

Grewal (2017) reported that although pesticides offer protective benefits against pest-related crop loss, their excessive use in vegetable production significantly elevates residue levels in food. This concern is supported by (Li *et al.,* 2023)**,** who found that dietary intake of pesticide-contaminated food contributes nearly five times more to human exposure than other routes like air or drinking water. Additionally, Amqam *et al.* (2019) confirmed that chlorpyrifos, a commonly used pesticide, poses high toxicity risks to human health.

2.3. Ill effects of residues

2.3.1. Residue accumulation

Residue analysis conducted in Burkina Faso (Dione *et al.,* 2023) detected lambda-cyhalothrin, profenofos, and chlorpyrifos-ethyl in tomato samples, with chlorpyrifos-ethyl exceeding MRLs, although the estimated risk of acute poisoning was considered low based on short-term dose models. Similar findings from India reported by Tripathy *et al.* (2022) showed frequent detection of acetamiprid and chlorpyrifos in tomatoes collected from Northern and Western regions. Dione *et al.* (2023) observed that most adverse effects linked to acetamiprid and lambda-cyhalothrin occurred when tomatoes were treated at or above the recommended dosage. Singh *et al.* (2017) emphasized that such residue accumulation in food products poses both acute and chronic health threats, including carcinogenic, oncogenic, genotoxic, and teratogenic effects in humans

2.3.2. Nutrient depletion

Abrokwah *et al.* (2019) reported that the application of acetamiprid and lambda-cyhalothrin on tomato and onion crops led to notable disruptions in their biochemical composition, indicating that pesticide exposure can negatively impact the nutritional quality of treated vegetables.

2.3.3. Pest resistance

Monitoring studies (Roy *et al.,* 2019; Fagundes *et al.,* 2025) in vegetable crops have revealed escalating pesticide resistance in major pests. For instance, Roy *et al.* (2019) documented that *Bemisia tabaci* populations in Indian vegetable farms exhibited reduced sensitivity to conventional and newer insecticides, leading to poor control efficacy. In Tamil Nadu, Kathirvel *et al.* (2025) reported that *Tetranychus urticae* (two-spotted spider mite) from vegetable fields displayed extremely high resistance up to 452-fold to acaricides like spiromesifen and buprofezin. These findings highlight that residue accumulation contributes to resistance development, undermining both pest management efficiency and farmer livelihoods.

3. Health impacts

Occupational exposure in vegetable farms has been associated with both acute and chronic health effects. (Sangamithra & Kumar, 2017) documented that farm workers frequently experience symptoms such as headaches, nausea, dizziness, and skin irritation immediately following pesticide application. This finding is corroborated by Kafle *et al.* (2021**)**, who reported that 73% of vegetable farmers in Chitwan, Nepal, experienced headaches, skin rashes, and respiratory issues, with only 8% seeking medical help. Moreover, these incidents contribute to a global estimate of approximately 3 million poisoning cases and up to 220,000 deaths annually in developing countries (Worst Polluted database; WHO estimates). Farmers in India are particularly vulnerable, as unsafe practices during pesticide application are widespread. Singh *et al.* (2017) observed that both acute toxicity and fatal poisonings occurred when pesticides were handled improperly or without adequate knowledge of their effects. In Nepal, Gurung and Kunwar (2018) found that 93% of vegetable farmers were unaware of chronic health risks associated with pesticide use, with many reporting engaging in hazardous behaviours such as smoking or chewing tobacco during spraying practices that further elevate absorption rates (Sabran, S. H., & Abas, A. (2021). Chronic health outcomes are equally concerning. (Kumar & Sinha, 2024) identified elevated oxidative stress and hepatic dysfunction among farmers with long-term exposure. Meanwhile, global reviews, including Scorza *et al.* (2023), have underscored links between occupational exposure and systemic effects such as endocrine disruption (Dhankhar & Kumar, 2023), neurodegenerative diseases, reproductive impairments (Coppola *et al.,* 2025), and several cancers. This section outlines the major types of pesticides commonly used in vegetable production, along with their associated health risks. It is widely recognized that the farm workers are at the highest risk of occupational exposure of pesticides, facing adverse health effects due to inappropriate protective measures, including inadequate clothing, pilferage, drift of spray droplets, leak and other defects in spray equipment, or other reasons and here we see the impact on human health (Tudi *et al.,*2022).

3.1. Neurological Symptoms and Diseases

3.1.1. Peripheral pain and headaches

A research study performed by Supangat *et al.* (2024) indicated a significant correlation between pesticide exposure and neurological issues, with 47% of respondents reporting neurological signs such as headaches and peripheral pain. According to a study by Devegappanavar (2020), 25.3% of farmers had a headache as a common symptom of pesticide exposure.

3.1.2. Alzheimer's disease

Long-term pesticide exposure has been associated with adverse neurological effects, in particular increased risk of Alzheimer's Disease (AD). Yan *et al.* (2016) summarized literature indicating chronic pesticide exposure may damage the brain and increase or hasten the onset of AD. Importantly, the Canadian Study of Health and Ageing (1994) reported that pesticides were a risk factor, as AD subjects were also found to have greater concentrations of DDE in the blood compared to non-AD subjects. Recently, (Ruiz-González *et al.,* 2024) investigated 40,044 hospital records from 2000-2021 in Andalusia, Spain, by means of a cross-sectional study, and confirmed the previous associations between outdoor pesticide exposure and higher risk of AD in the general population by demonstrating that areas with a higher number of pesticides had significantly greater prevalence and risk of AD (odds ratio analysis).

3.1.3. Parkinsons disease

Past research has also suggested an association between insecticides and herbicides and increased risk of Parkinson's disease (PD), and there was a significant association found for insecticides and herbicides with the greatest associations for organochlorines and organophosphorus. (Höllerhage, 2025) also revealed no associations in their studies looking at living or working on a farm or drinking well water in regard to PD. (Arellano *et al.,* 2026) expanded on prior research that identified an association between agricultural density and the presence of PD in the Northern Great Plains. Previous research simply used cropland density as a proxy for pesticide exposure. In the present research, some pesticide classes explained the association. This additional evidence identified that environmental exposure to pesticides did contribute and serves as a risk factor for Parkinson's disease.

3.1.4. Neurotoxic effects

Gargouri et al. (2018) demonstrated that certain pesticides, particularly pyrethroids and organophosphates, induce oxidative stress in the nervous system by generating reactive oxygen species (ROS) and disrupting antioxidant defense mechanisms. This oxidant-antioxidant imbalance contributes to neuronal damage, altered cellular function, and may accelerate the development of neurodegenerative diseases.

3.1.5. Cognitive effects

Akhoundzardeini *et al.* (2021) reported a potential relationship between greenhouse employee exposure to pesticides and cognition. Various cognitive performance measures were examined (memory, attention, and reaction time), and the results indicated a significant decline in performance in the workers who were exposed to pesticides relative to those who were not. These findings suggest that there may be an impact of long-term occupational exposure to pesticides, even in confined spaces like greenhouses, on neurological function and acceleration of cognitive ageing. The authors recommended protective measures to reduce pesticide-induced neurotoxicity and recommended regular neuropsychological assessments in high-risk occupational cohorts.

3.2. Cancer

Certain agricultural pesticides can also harm breast tissue DNA and block oestrogen receptors, increasing the risk of cancer and gene alterations, especially in vulnerable people (Sasikala *et al*., 2023). It is believed that new generation pesticides contribute to hormone-related diseases, including breast and colon cancer, by disrupting endocrine systems. They are also associated with poor reproductive health. According to Cazagranda *et al.* (2026)**,** the idea is supported by recent research on the link between pesticide exposure and brain tumours, particularly meningioma and other central nervous system tumours. Furthermore, several herbicides have been linked to an increased risk of liver cancer, while the precise processes remain unclear.

3.3. Reproductive issues

According to Fucic *et al.* (2021), infertility was significantly more likely to occur among women who used herbicides during the two years before to becoming pregnant. Karlsson *et al.* (2021**)** extended concerns regarding reproduction by reviewing 15 studies from nine different nations and consistently linking pesticide exposure to an increased incidence of congenital abnormalities. In order to highlight the possible teratogenic effects of exposure to agricultural pesticides, congenital malformations such as eye deformities, limb malformations, orofacial clefts, and urogenital abnormalities were explored. The Ontario Farm Study's results indicated crucial periods when pesticide exposure is most harmful. According to (De Souza Pomacena *et al.,* 2025)**,** preconception exposure was associated with early first-trimester abortions, but postconception exposure was associated with late spontaneous abortions.

3.4. Allergies

Pesticides can enter the human body by inhalation, ingestion, and skin absorption, and the amount absorbed is dependent on the physical properties of the chemical - solid, liquid, or gas (Hoppin, 2017). Almost half of farmers in the same study stated that they would rinse their eyes with water if they accidentally spilled pesticides, and 45.7% of them acknowledged that pesticides could enter the body by the mouth, nose, skin, and eyes. Skin discomfort was cited by most of the 265 farmers polled in a Devegappanavar (2020) study as a common sign of the detrimental health impacts of pesticide exposure.

3.5. Psychological issues

Psychological symptoms have been reported in individuals exposed to pesticides, including stress (24.2%), depression (15.3%), anxiety (44.7%), sleep disturbances (39.5%), and episodes of difficulty walking (8%); anxiety symptoms (56.2%) are most common among individuals 46 years and older (Kori *et al.,* 2018). In a study conducted by Buralli *et. al.* (2020**),** respondents were asked to note whether they experienced 23 acute symptoms recognized as being associated with pesticide poisoning. They found that helpers were more likely to report mental health symptoms with the SRQ-20 questionnaire. There were statistically significant differences between occupational groups with regard to poor sleep, fatigue, feelings of worthlessness, and reported inability to play a useful part. Khan *et al.* (2019) note that farmers living in high-income countries (i.e., the US, England, South Korea, and Spain) exposed to pesticides reported higher rates of mental health effects, notably depression, anxiety, and attempted suicide.

Table 2 – Major pesticides and its impact

Health Risk	**Pesticide Class**	**Reference**
Headache	Organochlorine	Jayaraj *et al.* (2016) **;** (Meenakshi *et al.*,2022) (Karki & Dangol, 2023)
Dizziness	Organophosphate	Thammachai *et al.* (2022); Pengpan *et al.* (2024) ; Curl *et al., (2020); (Karki & Dangol, 2023)*
Excessive Sweating	Carbamate	Pengpan *et al.* (2024) ; (Karki & Dangol, 2023)
Numbness	Organophosphate	Thammachai *et al.* (2022) ; (Curl *et al.,* 2020)
Eye Irritation	Dithiocarbamate	Pengpan *et al.* (2024)
Blurry Vision	Organophosphate	Thammachai *et al.* (2022) ; (Karki & Dangol, 2023)
Impaired Brain Development (Fetus)	Organophosphate	(Dhananjayan & Ravichandran, 2018)
Asthma	Organophosphate	Pengpan *et al.* (2024) ; (Dhananjayan & Ravichandran, 2018)
Cough	Organophosphate	Meenakshi *et al.* (2022)
Dyspnea	Carbamate	Pengpan *et al.* (2024)
Nausea	Organophosphate	Meenakshi *et al.* (2022)
Fatigue	Carbamate	(Thammachai *et al.*2022); Pengpan *et al.* (2024)
Vomiting	Chlorophenoxy	(Dhananjayan & Ravichandran, 2018) , Buralli *et al* 2020
Abdominal Pain	Organophosphate	(Dhananjayan & Ravichandran, 2018)
Systemic Poisoning	Organochlorine	Jayaraj *et al.* (2016)
Diarrhea	Organophosphate	Pengpan *et al.* (2024); (Thammachai *et al.,*2022)
Dermatitis	Carbamate	Pengpan *et al.* (2024)
Skin Irritation	Dithiocarbamate	Pengpan *et al.* (2024); (Karki & Dangol, 2023)
Blisters	Organophosphate	Meenakshi *et al.* (2022)
Infertility	Organophosphate	(Dhananjayan & Ravichandran, 2018)
Birth Defects	Organochlorine	Jayaraj *et al.* (2016)
Fetal Deaths	Organophosphate	(Dhananjayan & Ravichandran, 2018)
Miscarriage	Carbamate	Pengpan *et al.* (2024)
Carcinogenic Risk	Triazine; Organophosphate	(Dhananjayan & Ravichandran, 2018)
Parkinson's Disease	Mixed	(Curl *et al.,* 2020)
Neuroinflammation	Organochlorine	Song *et al.,(*2023) ; (Curl *et al.,* 2020)
Muscle Weakness /Cramps	Organochlorine	Jayaraj *et al.* (2016)

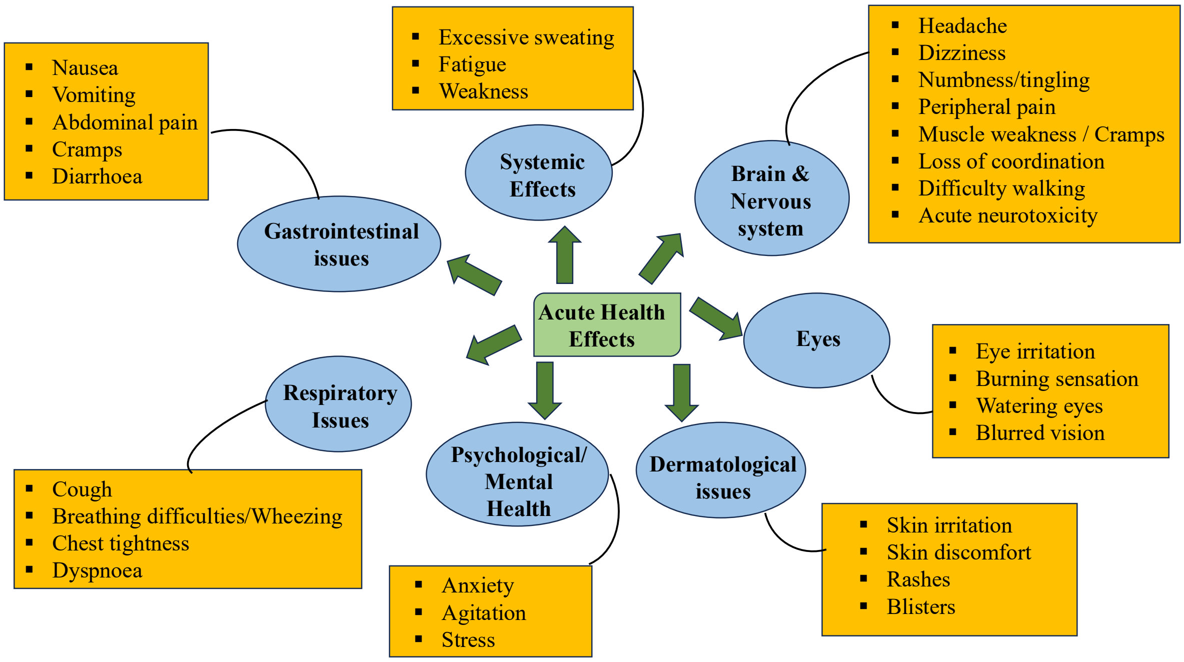


Figure 3 – Acute health effects

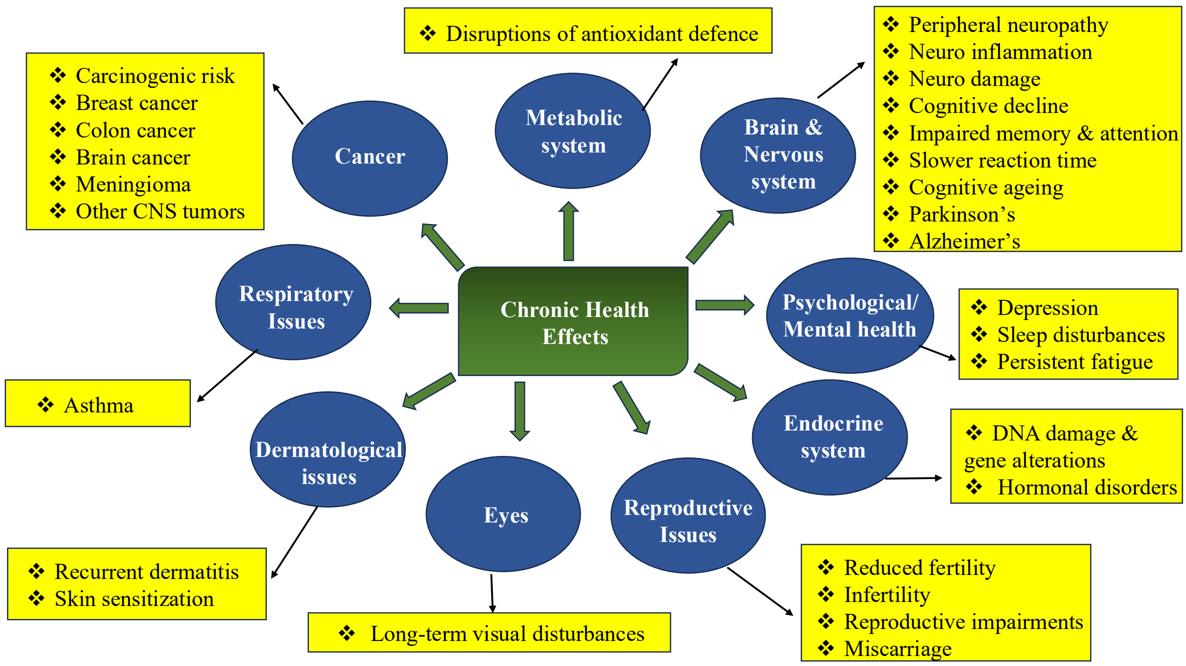


Figure 4 – Chronic health effects

WAY FORWARD

Recent findings emphasize the need for safe application protocols on farms and structured efforts to minimize pesticide residues in food . Research also supports the development of pesticide-specific washing methods such as using acidic solutions or ozone-treated water for crops like tomatoes to effectively reduce residue levels prior to consumption**.** At the retail level, strengthening quality control measures remains critical, especially in informal markets where produce often bypasses residue checks. Moreover, offering targeted incentives could support farmers in transitioning from synthetic pesticides to bio- pesticides and organic alternatives. This review underscores the urgent need for a multi-pronged approach to reduce pesticide reliance and its chronic health impacts on farming communities. A foundational strategy involves the introduction of structured training programs focused on pesticide toxicity, exposure pathways, and safe handling practices. These programs should equip farmers with the knowledge required for informed decision-making, emphasizing safe application intervals, personal protection, and alternatives to high- risk chemicals. Public health interventions must also be prioritized. These include policy support for sustainable practices, regular medical screenings in high-exposure zones, and the enhancement of rural health infrastructure to ensure timely diagnosis and treatment. Identifying vulnerable groups, such as women, children, and long-term applicators, is essential for targeted outreach. To enable real-time monitoring, developing a comprehensive village-level surveillance system is critical. Leveraging big data platforms can help track pesticide application trends and potential contamination hotspots, offering predictive insights for preventive action. Annual data collection at the local level can inform adaptive regulations and guide safer agricultural practices. In addition, policy efforts should support transparency in labeling, allowing consumers to make informed choices based on pesticide usage. India's alignment with global Maximum Residue Limit (MRL) frameworks should be further strengthened through international collaboration, ensuring consistency and compliance across export markets. Financial incentives such as subsidies for integrated pest management (IPM) tools and biopesticide adoption can ease the transition toward sustainable farming. Enforcement of stricter pesticide usage laws, coupled with consumer education on dietary exposure, will help bridge the gap between production efficiency and food safety. A balanced focus on yield, farmer livelihoods, and public health is critical. Expanding food safety regulations beyond farming practices to include health indicators will promote a more inclusive approach. These comprehensive strategies are key to building a future where agricultural productivity coexists with environmental and human well-being.

CONCLUSION

Pesticide use in vegetable production is unregulated or poorly regulated, creating serious risks to human health and food safety. In this research project, we have found that it is not just a quantity issue, but also a quality one. Unsafe application methods, disregard for safety intervals, and weak consumer-based regulations continue to accumulate residue on commonly consumed vegetables. Despite decades of experience, many farmers are still untrained and without equipment that protects them from chronic poisoning. The health effects are varied – from headache and dizziness immediately after contamination to more serious long-term effects including some cancers, infertility, and cognitive impairment. Moreover, pesticide residues have been shown to decrease the nutritional quality of the crop and encourage insect resistance and therefore increase the level of toxins applied continuously to the crops. Tackling these challenges requires a systematic response. Policies must tighten the implementation of Maximum Residue Limits (MRLs) and develop routine retail inspections, promote sustainable pest management practices including integrated pest management (IPM) and bio-pesticides through subsidization and incentives, and invest in farmer education programs and health checks, and rural health services. Further, to combat the harmful cycle of toxic harvests and move towards a safe and resilient agricultural future, governments, farmers, and consumers must work in collaboration.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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