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TOXIC FOOT PRINT OF CHEMICALS: IMPACTS ON SOIL QUALITY, WATER RESOURCES, AND BIOTIC COMMUNITIES

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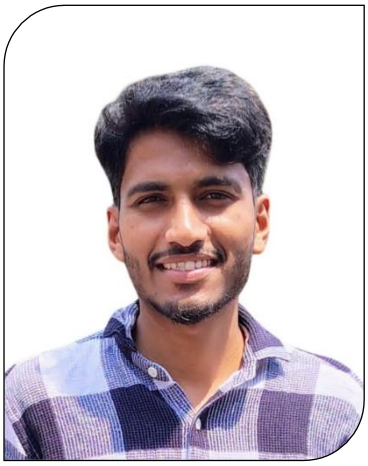

ABSTRACT

The green revolution in India, launched in the mid-1960s, represented a pivotal shift in agricultural production by introducing high-yielding, input-responsive crop varieties supported by expanded irrigation and intensive nutrient management. This transformation helped convert India from a food-deficient nation into a major food producer. However, the productivity gains were largely dependent on extensive use of synthetic fertilizers, pesticides, and herbicides. Over time, their indiscriminate and continuous application has led to ecological challenges, including pest resistance, secondary pest resurgence, chemical residues, non-target toxicity, and declining soil health. Consequently, systematic risk assessment is essential for sustaining agricultural productivity and environmental safety.

KEYWORDS: Green revolution, synthetic fertilizers, pesticides, herbicides, toxicity

INTRODUCTION

Agrochemicals—including fertilizers, pesticides, herbicides, fungicides, and plant growth regulators—have been central to increasing agricultural productivity and food security since the Green Revolution introduced input-responsive high-yielding varieties (Pingali, 2012). However, their intensive and prolonged use has fostered chemical-dependent farming systems with significant environmental consequences. After application, agrochemicals disperse through runoff, leaching, volatilization, and atmospheric transport, leading to accumulation in soil, water, and air. Excess nitrogen fertilization causes soil acidification, nutrient imbalance, and microbial disruption, while persistent pesticides and associated contaminants reduce soil biodiversity, suppress beneficial organisms, and impair long-term soil fertility and ecosystem functioning (Tilman et al., 2002).

Agrochemical residues also contaminate water bodies and the atmosphere, resulting in groundwater nitrate pollution, aquatic toxicity, eutrophication, biodiversity loss, and emissions of ammonia, nitrous oxide, volatile organic compounds, and particulate matter. These pollutants degrade air quality and contribute to climate change. Biological systems, including pollinators, natural enemies, wildlife, and humans, are vulnerable to acute and chronic toxicity, such as reproductive, endocrine, and neurological disorders (Kim et al., 2017; Chandrasekar et al., 2022). These concerns underscore the need for sustainable strategies, including integrated nutrient and pest management, ecological intensification, and safer agrochemical alternatives to balance productivity with environmental and human health protection.

HOW AGROCHEMICALS REACH ENVIRONMENT?

Agrochemicals enter the environment through multiple interconnected pathways immediately after application, including spray drift, volatilization, runoff, leaching and soil erosion. During spraying, off-target drift and volatilization transport chemicals into the atmosphere, where they may undergo long-range movement before redeposition. Rainfall or irrigation facilitates surface runoff, carrying dissolved chemicals and pesticide-bound soil particles into nearby water bodies, while water-soluble compounds such as nitrates and certain pesticides leach

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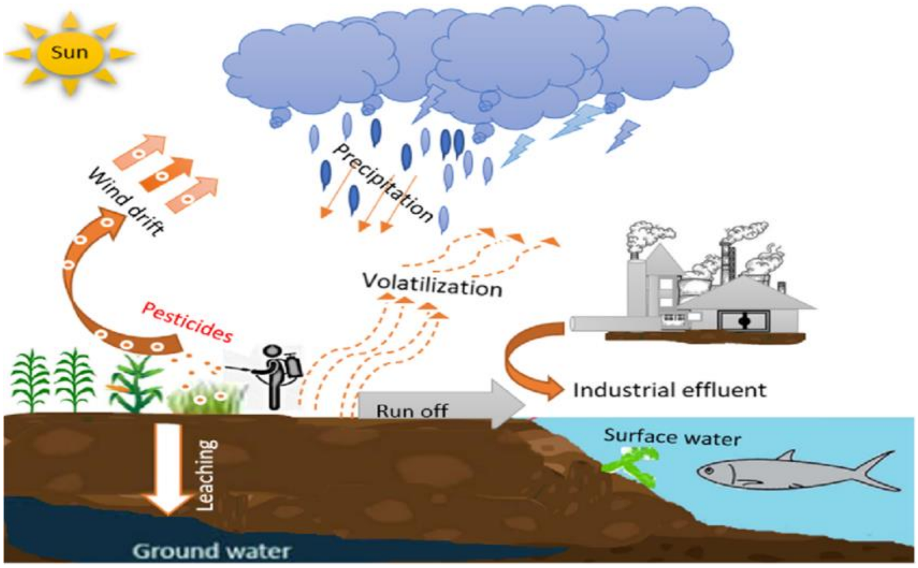

Figure. 1: Agrochemicals reaching environment

through soil profiles into groundwater. Many agrochemicals adsorb to clay and organic matter and are subsequently transported with eroded sediments, accumulating in aquatic systems and food webs; improper handling, spills and unsafe disposal further intensify soil and water contamination, often contributing to eutrophication. The environmental fate and mobility of these chemicals are governed by their physicochemical properties (solubility, sorption coefficient, vapor pressure and persistence) and soil characteristics (texture, organic carbon, pH and microbial activity). Persistent residues and metabolites can remain in soils and sediments for extended periods, disrupting microbial processes, impairing nutrient cycling and posing chronic risks to ecosystems and human health, demonstrating that agrochemicals rarely remain confined to their intended targets

BEYOND THE FIELDS: HOW AGRICULTURE BECAME A MAJOR DRIVER OF AIR POLLUTION

Agriculture contributes substantially to air pollution through direct emissions and secondary pollutant formation. Field operations and residue burning release large quantities of particulate matter, while diesel-powered machinery emits NO_2, black carbon, and primary PM, degrading air quality (Thai et al., 2024). Fertilizers, livestock, and agrochemicals are major sources of ammonia and VOCs, which promote secondary aerosol and ozone formation (Wyer et al., 2022). Nitrogen fertilization further drives nitrous oxide (N_2O) emissions, a potent greenhouse gas, with emission levels varying by crop, fertilizer type, and nitrogen dose, as shown in Table 1. These differences reflect interactions among fertilizer chemistry, soil aeration, and crop nitrogen dynamics, underscoring the need for precision nutrient management to mitigate atmospheric impacts (Pathak et al., 2010).

Table 1: Nitrous oxide emission from different crops

Crop	Fertilizers	N dose (kg ha^{-1})	N_2O emission (kg N ha^{-1})
	Urea	140	0.06
Rice	Ammonium sulphate	140	0.23
	Potassium nitrate	120	0.19
Wheat	Urea	140	0.71
Maize	Urea	120	0.64
Pigeon pea	Urea	40	0.37
Groundnut	Urea	60	0.46
Mustard	Urea	80	0.56
Chickpea	Urea	40	0.49

The standard limits of heavy metals in soils, fruits, and vegetables presented in Table 2 illustrate the chemical footprint of agrochemical use and associated inputs such as fertilizers, pesticides, wastewater, and soil amendments. Metals such as Pb, Cd, Hg and As**,** which often originate from phosphate fertilizers, synthetic pesticides, soil amendments and industrial contamination, persist in soil due to their low mobility and accumulate in edible plant parts, sometimes exceeding international permissible limits.

Indian and EU soil standards (e.g., Pb 250–500 mg/kg; Cd 3–6 mg/kg) and WHO/FAO food limits (Pb 5.0 mg/kg; Cd 0.2 mg/kg; Hg 0.03 mg/kg; As 0.5 mg/kg) underline the toxicological concern associated with chronic metal exposure. Essential micronutrients such as Zn, Cu, Mn and Ni**,** though required in trace amounts, can also reach phytotoxic levels when repeatedly added through agrochemicals, creating oxidative stress, suppressing enzyme function and impairing crop performance. The comparison of regulatory thresholds thus reflects how agrochemical-driven heavy-metal loading leaves a measurable chemical footprint, influencing soil health, food safety and long-term ecological sustainability (Mahawari et al., 2022).

Table 2: Standard levels of selected heavy metals (mg/kg) in soil, fruits and vegetables

Heavy metals	Soil		Fruits and vegetables	
	Indian Standard[55]	EU Standard[56]	Indian standard[55]	WHO/FAO Standard[75]
Pb	250-500	60	2.5	5.0
Cd	3-6	1	1.5	0.2
Hg	-	0.5	-	0.03
As	-	5	-	0.5
Zn	300-600	200		
Ni	750-150	50		
Cu	135-270	100		
Mn	-	-		
Cr	-	100		

A study conducted in the industrialized region of Solapur, Maharashtra, assessed heavy-metal contamination in 24 types of vegetables and fruits using ICP-MS and evaluated associated human health risks (Mahawari et al., 2022). The findings revealed detectable concentrations of Pb, Cd, As and Hg in edible crops, reflecting contamination of native soils influenced by agrochemical use and wastewater irrigation. Mean concentrations in vegetables Pb (0.344 mg kg^{-1}), Cd (0.043 mg kg^{-1}), As (0.004 mg kg^{-1}) and Hg (0.095 mg kg^{-1}) were close to or exceeded WHO/FAO permissible limits, with mercury levels notably surpassing safe thresholds. Although fruits showed comparatively lower accumulation, the presence of trace metals confirmed active soil–plant transfer and biomagnification pathways. The study highlights a growing disparity between regulatory standards and field realities, emphasizing the need for integrated nutrient–toxicant management and continuous monitoring to safeguard food safety and public health.

The Bureau of Indian Standards (BIS) drinking-water guidelines provide critical thresholds for chemical contaminants with known health implications, as summarized in Table 3. Parameters such as fluoride, nitrate, arsenic, and uranium pose significant public health risks when concentrations exceed acceptable limits, leading to dental and skeletal fluorosis, methemoglobinemia, carcinogenic effects, and renal toxicity. The absence of permissible relaxation for contaminants like nitrate, arsenic, and uranium highlights their toxicological severity. Electrical conductivity, though not a direct toxicant, serves as an indicator of salinity stress linked to cardiovascular complications. Together, the regulatory limits in Table 3 underscore the importance of sustained groundwater monitoring and mitigation to safeguard drinking-water quality.

Table 3: Indian Bureau of standards guidelines for contaminants levels in drinking water

Analyte	Unit	Acceptable limit	Permissible limit	Health effects
Chloride (Cl)	Mg/L	250	1000	Eye/nose irritation; stomach discomfort
Fluride (F)	Mg/L	1	1.5	Bone disease; children may get mottled teeth
Iron (Fe)	Mg/L	1	None	Anesthetic effect; promtes iron bacteria
Nitrate (NO_3)	Mg/L	45	None	Blue baby syndrome
Arsenic (As)	µg/L	10	No relaxation	Skin damage; increased risk of cancer
Uranium (U)	µg/L	30	No relaxation	Increased risk of cancer; kidney toxicity
Electrical conductivity (EC)	µS/cm at 25^0 C	750	3000	Anaesthetic effect; cardiovascular complication

BEYOND TARGET PESTS: BROAD-SPECTRUM AGROCHEMICAL EFFECTS ON BENEFICIAL INSECTS

Agrochemical exposure causes both acute and sub-lethal effects on pollinators, including honey bees and wild bees, resulting in impaired navigation, reduced foraging efficiency, and disruptions in learning and memory (Figure 2). Field and laboratory studies from India indicate that neonicotinoids and other commonly used insecticides reduce forager return rates, decrease pollen and nectar loads, and alter foraging behavior in *Apis* spp., ultimately lowering colony food reserves and fitness. Sub-lethal effects—such as compromised learning, reduced motor activity, and altered caste or brood development—often occur at concentrations below lethal thresholds. Consequently, repeated or chronic exposure can drive population-level declines even in the absence of visible mass mortality events (Chandrasekar et al., 2022).

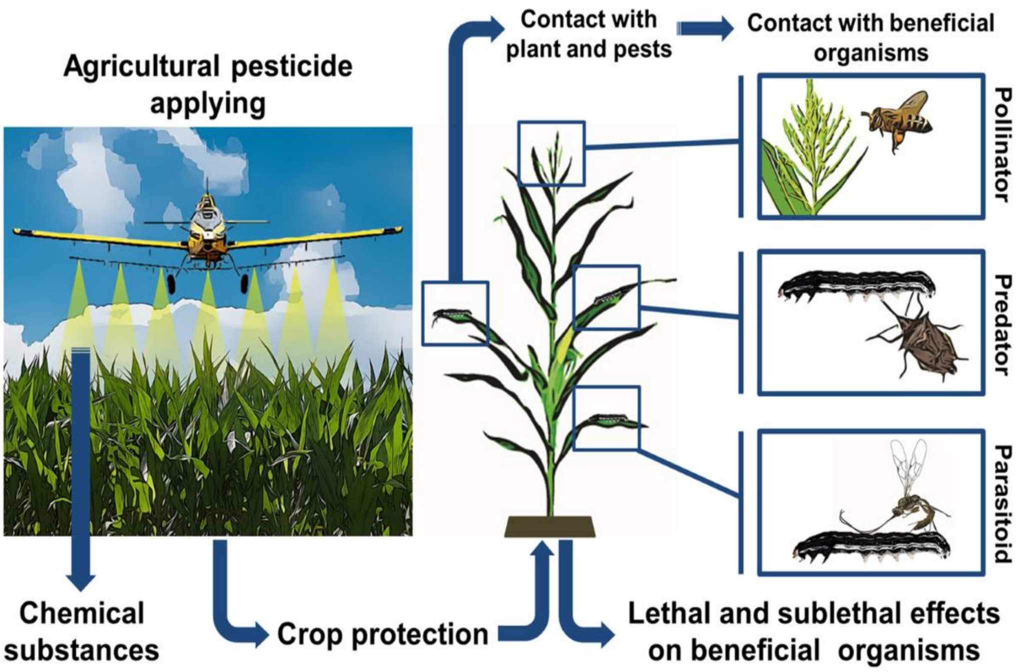

Figure 2: Agrochemicals effect on beneficial insects

PESTICIDES IN HONEY

Honey possesses multifaceted beneficial properties; however, environmental pollution and unregulated apicultural practices have contributed to its contamination. A study conducted in northern India employed the QuEChERS extraction method followed by chromatographic analysis using GC-μECD/FTD and GC-MS to determine 24 pesticide residues in 100 raw honey samples collected from diverse floral sources. Matrix-matched calibration demonstrated good selectivity and linearity ($r^2 > 0.99$), with limits of detection below 9.1 ng g^{-1} for all pesticides except monocrotophos (21.3 ng g^{-1}). Mean recoveries ranged from 86.0 to 107.7% with relative standard deviations below 20%, confirming method reliability. Pesticide residues were detected in 19.0% of samples, with dichlorvos, monocrotophos, profenofos, permethrin, ethion, and lindane being most prevalent. Honey from cotton, sunflower, and mustard crops showed significantly higher contamination (33.3%; $p < 0.05$) than honey from natural vegetation (13.5%), highlighting the need for systematic monitoring of pesticide residues in apicultural landscapes (Kumar et al., 2018).

TOXICOLOGICAL IMPLICATIONS OF AGROCHEMICAL USE ON HUMAN HEALTH

Pesticides are widely used to protect crops and commercial commodities, with nearly 1.8 billion people engaged in agriculture globally (Kumar et al., 2023). Their application reduces yield losses by controlling weeds, insects, and pathogens; however, increasing concern exists regarding their adverse effects on human health due to broad-spectrum and non-target toxicity. Human exposure occurs through occupational handling, spray drift, volatilization, contaminated food and water, with toxicity influenced by chemical properties, exposure duration, and environmental conditions (Kim et al., 2017). Since most diseases have multifactorial origins, no population group is entirely immune to pesticide-related health impacts. Globally, an estimated 385 million cases of occupational pesticide poisoning occur annually, resulting in approximately 11,000 deaths and affecting nearly 44% of the agricultural workforce, highlighting the substantial public health burden (Rogers & Rogers, 2024).

Chronic pesticide exposure has been linked to a wide range of health disorders, including neurological impairments due to cholinesterase inhibition, respiratory diseases such as asthma and chronic bronchitis, and dermal and ocular irritation among farm workers. Long-term exposure is also associated with endocrine disruption, reproductive toxicity, immune dysfunction, and increased risks of cancers, particularly leukemia and lymphoma. Additionally, bioaccumulation of pesticide residues can impair liver and kidney function through sustained metabolic stress. Collectively, these findings demonstrate that prolonged pesticide exposure affects multiple organ systems and underscores the need for safer handling practices, reduced chemical dependence, and strengthened occupational health protections in agricultural systems (Shekar et al., 2024).

CONCLUSION

The evidence synthesized across soil, water, air, biotic systems, and human health clearly demonstrates that agrochemicals leave a persistent and multidimensional toxic footprint in modern agriculture. Although fertilizers and pesticides have played a critical role in enhancing crop productivity and food security, their long-term and often unregulated use has led to nutrient imbalances, greenhouse gas emissions, heavy-metal accumulation, groundwater contamination, air-quality degradation, biodiversity loss, and rising chronic disease burdens among farming communities. Interactions among agrochemical properties, soil–water processes, atmospheric transport, and biological systems generate complex contamination cascades that extend well beyond the field scale. Mitigating these impacts requires a transition toward precision nutrient management, integrated pest management (IPM), safer formulations, improved regulatory oversight, and strengthened farmer awareness. Collectively, these measures can reduce ecological toxicity, protect human health, and align agricultural intensification with long-term environmental sustainability.

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