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Review Article

Mechanistic insights into how soil-borne contaminants impair plant physiology and agricultural output

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Abstract

Food security depends on agriculture, but excessive use of synthetic chemicals, such as pesticides and fertilizers, has resulted in the loss of soil nutrients and the build-up of new pollutants including microplastics and heavy metals. Reduced crop production and quality result from these pollutants' disruption of soil microbiota, degradation of soil health, and contribution to residue accumulation. Furthermore, excessive use of agrochemicals has increased production costs, necessitated more chemical inputs, and hastened the emergence of resistant insect populations. These issues are made worse by global climate change, which modifies soil conditions and increases pest pressure, ultimately lowering agricultural output and costing farmers money. Additionally, the presence of contaminant residues in agricultural produce frequently results in export rejection, which affects trade and the livelihoods of farmers. This review looks at how new toxins affect agriculture, emphasizing how they contribute to decreased production, environmental deterioration, and unstable economies.

Keywords: Synthetic chemicals, Agriculture crop productivity, Microplastic, Heavy metals, Climate change

Introduction

Agricultural output majorly focuses on these aspects, i.e., crop yield, nutritional quality, and phytochemical content, which ensures a holistic approach that benefits both food security by ensuring sufficient farm output to meet global demand, while vitamins, minerals, macronutrients, and Phyto molecules improve overall human health. Farm harvest is directly linked to the quality and productivity of the soil, which is the capacity to produce a specific crop under a particular nutrient management system (Seifu & Elias, 2018; Holz *et al.,* 2024). The presence and availability of sufficient essential nutrients in the soil for growing crops are affected by factors such as soil moisture, temperature, pH, physicochemical properties, microbiota, and the presence of toxic elements. Hence, only sufficient levels of nutrients in the soil do not ensure the quality and yield of the agricultural crop. Soil microorganisms play a vital role in converting nutrients from complex to simpler forms. These simpler forms of nutrients can easily be absorbed by the plant, thereby producing greater yields and boosting the nutritional value of the food. These nutrients also enable plants to produce beneficial phytonutrients such as antioxidants, which can improve the human immune system, hormone regulation, and overall health (Sbrana *et al.,* 2014; Halliwell, 2024). Continuous cropping is often practiced by farmers to achieve high yields for an economic benefit, which causes the depletion of essential nutrients in the agricultural field (Kartini *et al.,* 2024). To improve the nutritional value, farmers apply chemical fertilizers in the agricultural field. Similarly, pesticides are used in the field to control pests, which is the major cause of economic losses to crop yield and quality. But prolonged overutilization of chemical fertilizers and pesticides makes them major contaminants of agricultural fields (Sun *et al.,* 2021). Agricultural contaminants alter the biological, chemical, and physical properties of soil, reducing farm productivity and affecting human health (Mohanty & Das, 2023). Pesticides negatively impact the environment by contaminating soil and water. Furthermore, the impact on crop physiology by inhibiting reproductive organ development can affect seed and fruit production, reduce growth through inhibition of photosynthesis, cell division or elongation, and cause changes in carbon (C) and nitrogen (N) metabolism, which can result in reduced availability of nutrients required for plant growth (Mandal *et al.,* 2020). Moreover, the use of chemical fertilizers indirectly generates microplastics in fields because they are coated with plastic and designed for slow release, called controlled-release fertilizers (CRFs). Microplastics (MPs) have been found to enter soils not only through plastic-coated fertilizers but also through the application of mulches and sewage sludge, accumulating in different parts and acting as emerging pollutants that impede plant function (Bolan *et al.,* 2024). The stress of this contamination is modified for important physiological processes such as ion balance, oxidation, mutual adjustment, and photosynthesis (Katsumi *et al.,* 2021). MPs also affects the growth of roots and absorption of basic elements due to direct interaction with the roots of plants (Bosker *et al.,* 2019; Guo *et al.,* 2022). Furthermore, chemical emissions cause global climate change, primarily through changes in temperature and precipitation, which increases the occurrence of harmful agricultural pests and directly affects crop yields (Balbus *et al.,* 2013). Repeated and excessive use of synthetic fertilizers and pesticides also introduces heavy metals such as cadmium (Cd), lead (Pb), and arsenic (As) into agricultural soils. These heavy metals accumulate in plant parts such as roots, stems, leaves, fruits, etc. The major concerns impeding the development of an economically acceptable agriculture are nutrient deficiencies, heavy metals, and pesticide residues in agricultural products (Li *et al.,* 2020). Biotic factors, such as plant genotype, physiological state, soil biota, and abiotic factors such as chemical properties of pollutants and environmental disturbances, influence the uptake and accumulation of contaminants by crops. Studies have shown that leafy vegetables have the greatest ability to absorb and store pollutants, followed by root vegetables, grains, feed crops, and fruit vegetables (Huang *et al.,* 2020). This review highlights that agricultural pollutants can disrupt plant physiology and molecular functions, significantly reducing crop harvest and quality. Their presence in soil-plant systems poses a challenge for agriculture, underscoring the need for ongoing research, monitoring, and regulatory efforts to mitigate these impacts.

Impact of chemical pesticides on crops

Chemically derived compounds/molecules that are used to control or eliminate pests like insects, weeds, nematodes, fungi, and rodents are known as pesticides (Naeem *et al.,* 2023). Pesticides are classified into four groups according to the chemical formula: organochlorines, organophosphates, carbamates, and pyrethroids (Sharma *et al.,* 2019). Synthetic chemicals have a significant role in increasing the agricultural output by eliminating the risk of pests, as well as in leading commercial, food-based industries, including aquaculture, agriculture, food processing, and storage. At the same time, their overexposure from plants to soil or vice versa and their non-degradable nature have a negative impact on crops (Zhang *et al.,* 2021). The total amount of agricultural pesticide usage in 2022 is 3.7 million tons (MT), which increased by 4% compared to 2021, an increase of 13 % in 10 years (FAOSTAT Report 2024) (Figure 1).

Some pesticides are non-toxic in nature, but with time, their bio-transformed molecules can become toxic. For instance, the non-toxic pesticide Dichlorodiphenyltrichloroethane (DDT) gets degraded into toxic compounds such as Dichlorodiphenyldichloroethylene (DDE) and Dichlorodiphenyldichloroethane (DDD) when exposed to sunlight (Ebsa *et al.,* 2024).

Impact of organochlorines on crop quality

Organochlorine pesticides (OCPs) are synthetic chlorinated hydrocarbons having at least one chlorine atom with a covalent bond that is responsible for the chemical behaviour of the molecule or compound. Aldrin, dieldrin, endrin, chlordecone, dicofol, DDT, lindane, endosulfan, heptachlor, hexachlorobenzene, and pentachlorophenol are the different examples of OCPs (Martyniuk *et al.,* 2020). OCPs block the closure of sodium ion channels in the nerve cells of the insects, leading to prolonged depolarization of the nerve membrane, which results in repetitive nerve firing. This constant stimulation of the nervous system causes convulsions, paralysis, and eventually death in the targeted insect (Jayaraj *et al.,* 2016). OCPs are used for controlling agricultural pests, but they can also accumulate in the crops with time. OCPs are introduced into the plant directly by the application of the pesticide spray and move due to their lipid-soluble and water-insoluble nature, moving from the cuticle of plant leaves to the plant tissue to reach the plant root. Also introduced into the soil indirectly during spray and taken up by the plant root, and goes toward the other parts of the plant. OCPs are well-known environmental contaminants that contribute to ecological instability worldwide. Despite being banned globally, they are still used for controlling agricultural pests because of their high persistence, lipophilicity, and low aqueous soluble nature (Fosu-Mensah *et al.,* 2016). A study reported that 18 OCP residues were accumulated beyond the residual limits in the edible part of the crops like banana, brinjal, eucalyptus, lotus, paddy, sugarcane, and tomato, beyond the residual limit of the pesticide, face rejection for export (Chandra *et al.,* 2021). Due to pesticide residues, 200 tonnes of Indian basmati rice were rejected in 2021, which exceeded the national limits of countries like Egypt, Lebanon, and Yemen (The Indian Express, 2021).

Impact of organophosphates on crop yield

Organophosphorus compounds (OPs) are synthesized by esterification of phosphoric acid with alcohols.

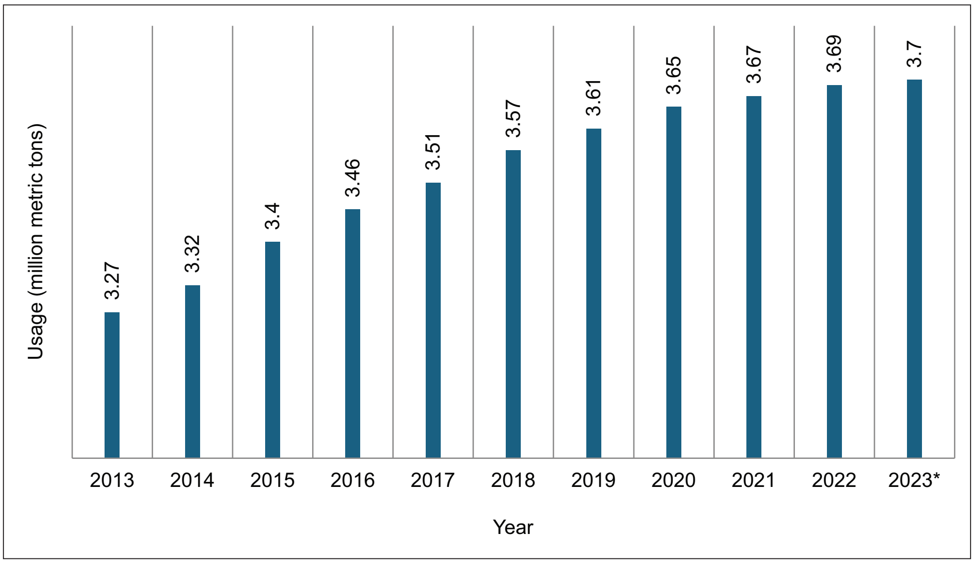

Figure 1: Data shows 10 years (2013 to 2023) worldwide chemical pesticide usage

There are many OP compounds used to control weeds and pests in agricultural crops, including diazinon, malathion, parathion, methyl parathion, fenitrothion, chlorpyrifos, dichlorvos, phosmet, tetrachlorvinphos, azamethiphos, and azinphos-methyl (Xie *et al.,* 2022). Among the different OPs, malathion is most widely used for crop protection by controlling insect pests. It inactivates the cholinesterase enzyme, which hydrolyses the neurotransmitter acetylcholine into choline and acetic acid, irreversibly binding to a serine residue in the active site of the enzyme, resulting in insect death due to nervous system failure (Bajgar, 2004). However, malathion caused oxidative stress-mediated cytotoxicity and phytotoxicity, adversely affecting crop yield. Reactive oxygen species (ROS) induce oxidative stress, which is mainly caused by alterations in the activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APXDH), and glutathione S-transferase (GST) (Tsai & Lein, 2021). These enzymes prevent the production of reactive oxygen. ROS causes enzyme inactivation, DNA and RNA damage, lipid peroxidation, cell membrane damage, and protein oxidation in the root of the plant. A study investigated the growth rate and cell division of Allium cepa root tips affected by malathion application and, as a result, reduced the mitotic division in cells of the root tip (Srivastava & Singh, 2020). Another study showed that excessive application of malathion at early planting caused phytotoxicity in *Solanum melongena* (eggplant) seedlings by the production of ROS due to effects on the activity of antioxidant enzymes, which resulted in oxidative stress (Yengkokpam & Mazumder, 2020). Similarly, a study reveals that a low dose of chlorpyrifos slightly disrupts plant physiology, but at a high dose, it could cause oxidative stress and inhibit the synthesis of protein and chlorophyll in the Rice crop plant (Mu *et al.,* 2022).

Carbamates' indirect impact on crop yield

Carbamate is the conjugate base of carbamic acid, which is produced after replacing the amino and carboxyl groups of carbamic acid with alkyl or aryl substituents. Developed compounds are carbaryl, aldicarb, carbofuran, etc. Carbamates are used for killing agricultural pests like aphids, whiteflies, and mealybugs. It acts upon the enzyme acetylcholinesterase, leading to the disruption of neurotransmission, important for proper nerve functioning (Chaturvedi, 2012). These chemical compounds prevent crop damage by reducing the harmful pest population, but simultaneously act upon beneficial organisms like honeybees, ladybugs, and spiders. These insects are the natural pollinators and predators that help in the proper pollination of crops and reduce harmful pest infestation (Iturbe-Requena *et al.,* 2020; Shivanna *et al.,* 2020). Misapplication or overuse of carbamate insecticide developed phytotoxicity in terms of germination efficiency rate, root and shoot growth, and oxidative stress that appeared in the crop plant. The researchers reported that increasing exposure concentrations of carbamate insecticide resulted in 69% phytotoxicity in cowpea seedlings, and the insecticide demonstrated ROS-mediated oxidative damage in the membrane lipids of cowpea root cells. Oxidative damage and cytotoxicity in different plants: Onion, Beetroot, Pea, Fenugreek, and Beans were also reported (Shahid *et al.,* 2021b). Over time, repeated use of carbamates can lead to the development of pesticide resistance in pest populations like aphids, which causes significant economic losses to agricultural commodities. Carbamate is hydrolysed by carboxylesterase E4 and FE4 before reaching their target site in aphids and developing resistance to the chemical. To eradicate resistant pests in agricultural land, frequent application and higher concentrations of pesticides are required, which increases the production cost of the final output and reduces the final yield of the crop (Hawkins *et al.,* 2019; Kaleem Ullah *et al.,* 2023).

Pyrethroids' impact on fruiting and flowering of the crop

Pyrethrin is a natural insecticidal compound extracted from the chrysanthemum flower and is nontoxic, but a structurally similar compound that is synthesized chemically, called pyrethroid, is widely used in horticulture and agricultural land for controlling harmful insect pests. It causes continuous nerve impulses, paralysis, and death in pests by targeting voltage-gated sodium channels, keeping them open for longer periods (Ensley, 2018). Because of the broad-spectrum action of this chemical compound for controlling pests, various types of agricultural farmers utilize it in inappropriate ways. Its improper use not only eradicates the target pest but also eliminates nontargeted natural predators like ladybird beetle, bug, wasp, etc., of agricultural pests, and the natural pollinators like honeybees (*Apis mellifera*), that were required for pollination, are a crucial step for the development of fruit and seed. World's 35% of the food crops, like apples, blueberries, strawberries, peaches, almonds, coffee, etc., depend on natural pollinators to reproduce (Stanley & Preetha, 2016). Pyrethroids cause a reduction in the fruiting and flowering of the crop plant, which directly affects the crop productivity. The target insect pest develops resistance by overexposure to this synthetic chemical compound (Balanza *et al.,* 2021). It indirectly affects soil health by eradicating the soil microbiome, which plays an important role in providing nutrients to plants in an available form. Nutritional deficiency affects plant growth and ultimately the yield and quality of crops (Ankit *et al.,* 2020).

Other chemical pesticides' impact on crop immunity

Crop physiology is impacted by the improper development of reproductive organs, growth reduction, and lower nutrient availability for plant growth due to the excessive use of pesticides. The effect on crop development partly depends on the type of pesticide used. But herbicides might also affect soil microorganisms by interfering with metabolic and enzymatic activities, such as reducing the activity of the dehydrogenase enzyme, which can affect the nutritional quality of the soil. It was noted that the application of the herbicide 2,4-D resulted in the highest reduction in soil dehydrogenase (DHA) activity by 58.24% compared to OPs like chlorpyrifos, carbamates like carbofuran

(Arora *et al.,* 2019). Researchers found that glyphosate is a target nonspecific organophosphorus herbicide used for controlling broadleaf weeds and grasses by disrupting the shikimic acid pathway through inhibition of the enzyme 5-enolpyruvylshikimate 3-phosphate synthase (EPSPS) that resulted in reduced biosynthesis of aromatic amino acids and alterations in protein metabolism, thereby leading to plant death (Gravena *et al.,* 2012; Choudhury, 2019; Vázquez *et al.,* 2021). Excessive use of this herbicide indirectly affected the agricultural crops by impacting similar shikimic acid pathways that are responsible for the development of phenolic compounds like tannin, lignin, flavonoids, and alkaloids. These compounds have a significant role in developing plant immunity. Reduction in the development of phenolic compounds plants becoming more susceptible to soil-borne diseases and agricultural pests (Gomes *et al.,* 2015; Santos *et al.,* 2024). Furthermore, this herbicidal compound exhibited antagonistic effects on the uptake and transport of trace elements such as iron (Fe) and manganese (Mn) in plants. Studies have shown that sub-herbicide doses reduced the uptake and transport of micronutrients in sunflower and soybean plants. Due to the presence of carboxyl and phosphonate groups, glyphosate can complex with metals and chelate them, reducing the absorption and transport of trace elements (Eker *et al.,* 2006; Cakmak *et al.,* 2009).

Impact of chemical fertilizers on plant metabolism

Chemical fertilizers are man-made chemicals that are used to maintain soil fertility and ensure high crop yields. Most developed synthetic chemical fertilizers, like urea, diammonium phosphate (DAP), and ammonium sulfate, contain N, phosphorus (P), and potash (K) (Sarwar *et al.,* 2020). The global demand for these nutrient fertilizers has considerably increased from 2013 to 2023 (Figure 2).

N is an essential element taken up by plants in the form of ammonium ($NH4^+$) and nitrate ($NO3^-$), which plays a critical role in various plant processes, including chlorophyll synthesis and micronutrient uptake by plants (Ma *et al.,* 2023). They are also used for the biosynthesis of important molecules such as signaling molecules, photosynthetic pigments, and secondary metabolites, as well as for the formation of proteins and nucleic acids (Guan, 2017; Lee *et al.,* 2020; Musacchio *et al.,* 2020; Liu *et al.,* 2022). Similarly, P is another important nutrient and is generally occupied by phosphate-shaped plants that play a significant role in energy transmission, cell division, DNA synthesis, and phospholipid synthesis. It also adjusts physiological reactions and increases the resistance of plant non-biological stress, such as heat, salt, drought, sampling, high carbon dioxide (CO_2), and heavy metal toxicity (Du *et al.,* 2020; Kumar *et al.,* 2020; Lambers, 2022; Khan *et al.,* 2023; McDowell *et al.,* 2023). Similarly, K is an activator of key enzymes in protein synthesis, sugar transport, N and C metabolism, and photosynthesis (Oosterhuis *et al.,* 2014). The optimal concentration of NPK fertilizers improves not only yield but also the nutritional quality of crops. Overuse of these nutrients can lead to imbalanced growth and reduced crop yield and quality. The protein content increases at an optimal level of N, but beyond its optimum limits, protein content reduces. An investigation showed that increased N application leads to higher protein yield and accumulation of specific proteins such as prolamin and glutelin, but excessive concentration of N reduces NO_3 reductase and glutamine synthetase enzyme activity, which leads to a decline in accumulation of specific amino acids in buckwheat (Wan *et al.,* 2023). Similarly, a study showed that optimal K improved sugar and starch concentrations in pearl millet grains through carbohydrate metabolism via the activity of ribulose-1,5-bisphosphate carboxylase oxygenase (Rubisco) and phosphoenolpyruvate carboxylase (PEPC), enzymes that assimilate CO_2 into organic carbon (Li *et al.,* 2022). Similarly, fructose-1,6-bisphosphatase (FBPase) catalyzes the sucrose synthesis pathway and stimulates sucrose synthesis via sucrose synthase (SuSy) and sucrose phosphate synthase (SPS). But high K levels can disrupt the photosynthesis enzyme activity by reducing the absorption of Mg and reducing sugar concentration in crops and impairing the plant's ability to efficiently translocate sugars from leaves to other parts of the plant,

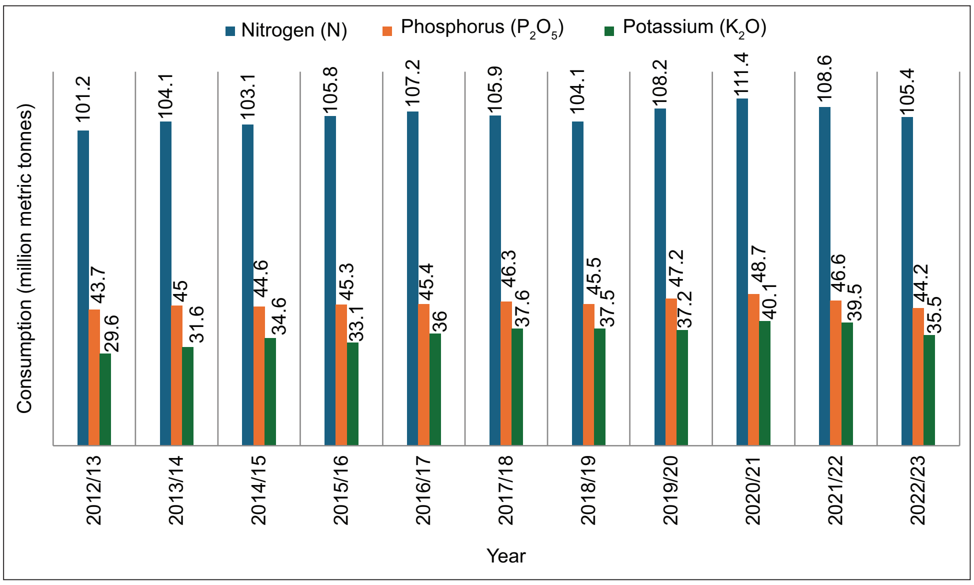

Figure 2: Data shows 10 years (2013-2023) Global chemical fertilizer consumption

such as fruits or tubers, leading to lower sugar accumulation (Garcia *et al.,* 2022). Increasing the concentration of K cations can also interfere with the absorption of essential cations like calcium (Ca) and magnesium (Mg) from soil, leading to nutrient imbalances. Unavailability of Mg and Ca cations reduces the structural strength, enzyme activity, photosynthesis, and energy production in plants (Xu *et al.,* 2020). Optimal P levels support strong root development, improving a plant's ability to access water and micronutrients, particularly Zn, Fe, and Cu, ensuring efficient energy transfer, fuelling growth and metabolic activities in plants, improving flowering and fruiting, and providing greater resistance to stress and disease. On the other hand, excessive P can lead to Fe and Zn deficiency in the plant. A study examined that under excess P, Arabidopsis showed a decrease in the development of primary root length and apical meristem, which are essential for the absorption of micronutrients, negatively affected by ethylene-mediated response (Shukla *et al.,* 2017).

Impact of microplastics on plant growth

MPs, tiny plastic pieces smaller than 5 mm, are insoluble in water and non-biodegradable in nature (Galloway *et al.,* 2017). In the last two decades, plastic production reached 368 million tons in 2019 and is expected to double in the next 20 years (Huang *et al.,* 2021). Asia is the biggest producer of plastic, contributing 187.68 million tons of plastic, followed by Europe with 58.88 million tons (Plastics Europe, 2020). 26% of the total plastic produced is recycled, and the rest is entering the environment, and improper disposal methods have led to plastic pollution (Azeem *et al.,* 2021). In different environmental conditions like temperature, pH, and humidity, plastics undergo fragmentation and decomposition and get converted into MPs, mesoplastics, and nanoplastics (Alimi *et al.,* 2018) and persist for hundreds of years in the environment (Duan *et al.,* 2021). The application of plastic-coated agrochemicals to soil directly releases MPs into the environment and indirectly affects the food chain. Scientists investigated the accumulation of microcapsules derived from coated fertilizer in paddy fields (Katsumi *et al.,* 2021). According to the European Chemicals Agency, intentionally added MPs are used to develop CRFs, which are made of plastics such as polyolefin and polyvinylidene chloride, which dispense their contents over time through osmotic pressure (Lawrencia *et al.,* 2021). In the European Economic Area (EEA), fertilizers, pesticides, and seed coatings account for almost half of the estimated 51,500 tonnes (metric tons) of MPs used annually. Specifically, it is estimated that 22,500 tonnes of MPs are used in fertilizers, 500 tonnes in pesticides, and 500 tonnes in seed coatings. This indicates that the agriculture sector in the EEA uses more MPs than any other sector, including cosmetics (CIEL, 2022). The first detailed study investigated those different sizes of plastic particles, which range between 50-5000 nm, reduced 78% of cress (*Lepidium sativum*) seed germination by blocking the pores in the seed capsule identified by confocal microscopy also present in the root hairs of the germinated seedling (Bosker *et al.,* 2019). Using confocal laser scanning microscopy and scanning electron microscopy, it was observed that MPs penetrated the root extracellular cortex, entered the stele, and were transported to the shoots via transpiration through xylem vessels. MPs' accumulation level was significantly influenced by the types of surface functional groups that were revealed by quantitative analysis. This means that MPs pose edible risks through transfer in the crop food chain, but bioaccumulation varies depending on the surface functional groups (Xu *et al.,* 2022). MPs reduced photosynthesis and chlorophyll content, impaired nutrient uptake, triggered phytotoxicity, enhanced oxidative damage, reduced shoot biomass, and decreased biomass production in rice (Wu *et al.,* 2020, 2021; Ma *et al.,* 2022). In the wheat, it impaired micronutrient content and reduced the shoot-to-root biomass ratio (Lian *et al.,* 2020). Impaired N and water uptake reduced overall growth in Maize (Urbina *et al.,* 2020). MP-induced physical growth reduction in plants was sustained by alterations in key physiological mechanisms, including photosynthesis, redox regulation, ionic homeostasis, and hormonal regulation. These mechanisms are sensitive to stressful conditions, and any disruption can lead to reduced crop growth (Jia *et al.,* 2023).

Impact of heavy metals on plants

Metals with atomic weights between 63.5 to 200.6 g/mol and densities above 5 g/cm^3 are called heavy metals: chromium (Cr), As, nickel (Ni), cadmium (Cd), lead (Pb), mercury (Hg), Zn, and Copper (Cu). Atmospheric precipitation, livestock manure, wastewater irrigation, pesticides, herbicides, phosphate-based fertilizers, and sewage sludge-based amendments are the main sources of heavy metal accumulation in agricultural soils Gall *et al.,* 2015; Lv *et al.,* 2015; Elgallal *et al.,* 2016; Woldetsadik *et al.,* 2017; El-Kady & Abdel-Wahhab, 2018). The NRAMP (Natural Resistance-Associated Macrophage Protein) and ZIP (Zinc Iron Permease- ZRT/IRT-like Protein) families of metal transporters are responsible for the transport of mineral elements, such as Zn, Mn, Fe, Cu, and Ca, also facilitate the uptake of heavy metals by plants (Yan *et al.,* 2020). Heavy metals generate free radicals, leading to increased levels of ROS in cells, causing oxidative stress and damaging proteins, nucleic acids, lipids, and enzymes in plants. As a result, it causes cell damage, and inhibiting enzyme activity can lead to the death of the entire plant. Seed germination and seedling development are significantly affected by heavy metals (Seneviratne *et al.,* 2019; Rizvi *et al.,* 2020). A study revealed that exposure to increasing doses of Cd reduced embryo development and seed germination in mung bean seeds because Cd inhibited the enzyme activity of α-amylase and protease in seedlings. These enzymes contribute to protein and starch hydrolysis to the effective mobilization of seed reserves for seed germination (Anwar *et al.,* 2021). Ca is the allosteric activator of the alpha-amylase substrate-binding site, which activates this site and allows the enzyme to interact with its substrates, such as starch, stabilizing the structure of alpha-amylase. This Ca is replaced by the Cd and affects the substrate binding site of the enzyme (Lin *et al.,* 2025).

Another experiment done in wheat showed that heavy metals reduce starch content, limit nutrient levels, inhibit PSII activity in chloroplasts, and induce the expression of heat shock proteins and proline. Proline accumulation indicates induced abiotic stress developed by heavy metals (Singh & Rathore, 2020). Cd interferes with the homeostasis of Fe, Zn, and Mn in cells by binding to sulfhydryl amino acids like cysteine. NRAMP family, OsNramp1 and OsNramp5, are responsible for the uptake of Fe, Zn, and Mn from the soil into roots, were significantly facilitates the accumulation of Cd in rice grains (Sasaki *et al.,* 2012; Zhang *et al.,* 2023). A study showed that, in mulberry leaves, the higher concentrations of Pb and Cd reduced leaf Chlorophyll-a content. Under Pb and Cd stress, the photosynthetic C assimilation capacity of mulberry leaves was reduced. Pb and Cd concentrations impaired NPQ (non-photochemical quenching), and chloroplasts promoted a great increase of ROS, resulting in a significantly higher degree of oxidative damage (Huihui *et al.,* 2020). Excessive amounts of Cr deposited in plant tissues inhibit the cell cycle, disrupt water and mineral balance, interfere with enzyme activity, impair N assimilation, and weaken the antioxidant system. Researchers found that Cr (VI) induced an array of genes related to ROS, Ca, mitogen-activated protein kinases (MAPKs), and calcium-dependent protein kinases (CDPK), all of which are key players in perception and signal transduction pathways in rice (Huang *et al.,* 2014). Cu is an essential micronutrient for plant enzymes that act in electron transport and catalysis of redox reactions in mitochondria and chloroplasts (Marschner, 2011). However, at toxic levels, Cu reduces the plant production and affects photosynthesis, causing reduced growth, promoting oxidative stress and reducing absorption of water and mineral nutrients (Moustakas *et al.,* 1997; Cambrollé *et al.,* 2015; Marques *et al.,* 2018; Nazir *et al.,* 2019).

Impact of contaminants on climate change, affecting crop yield

Climate is a set of key parameters, including temperature, precipitation patterns, atmospheric humidity, soil moisture content, and the condition of snow and ice cover. These variables collectively influence the long-term behaviour of the Earth's climate system, in which changes get triggered by emissions of greenhouse gases (GHGs), such as CO_2, Methane (CH_4), and nitrous oxide (N_2O), from the Earth's surface into the atmosphere (Mikhaylov *et al.,* 2020) which absorb heat radiation from the Earth's surface and re-release it in all directions, including back toward Earth's surface, thus trapping heat. The main sources of greenhouse gas emissions are electricity and heat (31%), agriculture (11%), transportation (15%), forestry (6%), and manufacturing (12%). Agriculture is a significant source of greenhouse gases (EPA, 2017). When synthetic N fertilizers are applied to soil, plants absorb only less than half of it, depending on the type of crop and soil conditions (Toleikienė *et al.,* 2019), while some are consumed by soil microorganisms, which generate 60% N_2O as a metabolic by-product of the nitrification and denitrification process (Kumar *et al.,* 2020). N_2O has 265 times more global warming potential compared to CO_2 (Wang *et al.,* 2023). Similarly, the emission of CO_2 and CH_4 from the burning of fossil fuels for electricity generation, heat production, and transport contributes 90% of the world's C emissions (Mikhaylov *et al.,* 2020). Greenhouse gases change the temperature of the Earth, by which water evaporates; at the same time, glaciers and sea ice melting actively lead to an increase in the ocean level, which causes floods in the coastal areas, affecting agricultural output (Bolan *et al.,* 2024). Direct effects of climate change, including increasing temperatures, altering precipitation patterns, and reducing water availability for irrigation, impact wheat yield losses in the Indo-Gangetic Plain (IGP), which is the main wheat-producing region in both India and the world. In November, when plants require substantial water during the sowing and germination phase, precipitation significantly decreased and slightly increased during the remaining season (Daloz *et al.,* 2021). This reduction can therefore cause considerable stress to the crop. Wheat flowering, which determines the number of grains and the amount of fruit set, gets negatively affected by an increase in temperature (Ullah *et al.,* 2024). Similarly, irrigated rice yields are declining due to rising temperatures and a shorter growing season. Rice yields are affected by temperature, length of growing period (LGP), precipitation, and CO2. If the temperature increases for a certain period and exceeds a threshold value, plant growth and development will be irreversibly impaired. Furthermore, crop biomass and yield will also be affected as temperatures increase due to a shorter LGP, due to a decrease in cumulative intercepted radiation. Changes in precipitation affect soil water balance, soil evaporation, and rice transpiration (Rahman *et al.,* 2017; Grotjahn, 2021; Kew *et al.,* 2021; Singh *et al.,* 2024). Changing precipitation patterns, more frequent droughts, and higher temperatures could result in up to 40% reductions in annual crop yields. The altered rainfall pattern, increased frequency of drought, and increased temperature can translate to a loss of up to 40% in annual crop yield (Rezaei *et al.,* 2023).

Impact of contaminants on Phyto biota, affecting crop quality

Soil organisms like bacteria, fungi, protozoa, and nematodes, symbiotically associated with plants, are called phyto-biota (Marcianò *et al.,* 2025). These organisms are essential for maintaining the soil quality by mineralization of nutrients. Mineralization is the process in which complex forms of nutrients convert into simpler forms, like plant residues and animal waste that convert into ammonia (NH_3) by ammonification reactions, into NO_3, sulfate, and phosphate by producing metabolites like enzymes and organic acids. This available form of nutrients is easily taken up by the plants (Zarabi & Jalai, 2012; Jacoby *et al.,* 2017; Elrys *et al.,* 2021; Bouhia *et al.,* 2022). Microbes like *Rhizobium, Azotobacter,* and *Clostridium* play an important role in nutrient cycling via N fixation in which atmospheric N gets converted into NH_3 and phosphate solubilization by *Pseudomonas* and *Bacillus* converts organic P into inorganic P. Soil fungi like, *Trichoderma*, decompose organic matter, releasing free C, N, and sulfur (Chen *et al.,* 2020; Aasfar *et al.,* 2021; Organo *et al.,* 2022; Soares *et al.,* 2023). Soil microbial community also helps in the production of phytohormones like auxin, gibberellins, and cytokinin, and siderophore production from bacteria like *Pseudomonas* (Hu *et al.,* 2017). Additionally, some microbes like *Bacillus* and *Pseudomonas* also alleviate stress like drought, salinity, and heavy metals in plants. Beneficial microbes also help in crop disease suppression by competing with pathogenic bacteria and fungi, which also induces systemic resistance in plants to cope with crop pests (Timofeeva *et al.,* 2024). Similarly, they also play a significant role by triggering and/or stimulating signalling pathways like salicylic and jasmonic acid pathways, which are responsible for the production of secondary metabolites like alkaloids, flavonoids, terpenoids, and phenolics that are not directly involved in plant growth and development but provide defence against pest and environmental stress (Pusztahelyi *et al.,* 2015; Eichmann *et al.,* 2021). The soil microbial community is affected by a toxic environment in the excessive presence of pesticides and chemical fertilizers. Bacterial growth, respiration, and membrane permeability are affected by the soil pH and organic matter content (Prashar & Shah, 2016; Arora *et al.,* 2019; Medo *et al.,* 2021). Researchers observed that *Sinorhizobium saheli* growth, morphology, and respiratory activity were severely affected by carbamate pesticide (Shahid & Khan, 2022). Similarly, it was reported that hexaconazole fungicide negatively affected the soil microbial community, N cycling in a paddy field (Ju *et al.,* 2017). *Enterobacter cloacae,* a phosphate-solubilizing bacterial growth, morphology, and biofilm formation negatively impacted by increasing doses of organochlorine pesticides (Shahid *et al.,* 2021a). In addition, propiconazole is a triazole fungicide that also affects soil fertility and microbial diversity. Study demonstrated that this fungicide at a dose of 15-20 kg/ha on red and chernozem soils reduced the activity of phosphatase and urease and reduced the populations of bacteria and fungi (Satapute *et al.,* 2019).

Concluding remarks and future directions

New crop varieties and various chemicals have been introduced to provide crops with nutrients and protect them from pests and diseases. Modern farming depends on technology, synthetic chemicals, and money, which have increased food production and controlled pests but led to economic, environmental, and social issues. The overuse of synthetic chemicals and technology in modern farming has led to global climate damage in many parts of the world. One of the biggest issues is emerging contaminants in soil, reducing its quality, which is essential for productive agriculture. The current studies on the negative impact of these chemicals on plants are still limited. According to available literature, they have found that crop plant physiological processes are directly or indirectly severely affected by this unsustainable agriculture, leading to a reduction in crop yield and quality. It also affects soil-living organisms, which are directly or indirectly important for maintaining soil productivity. The negative impacts can range from temporary to long-term or may cause irreversible damage. However, more studies should be performed at the biochemical, anatomical, and molecular levels to evaluate the mechanism of toxicity of each soil contaminant on plants. Futuristic approaches like nanotechnology, combined biological remediation technologies, and precision farming are required to manage or eradicate these molecules from agricultural soil. For the removal of hazardous contaminants, cost-effective, eco-friendly sustainable agriculture practices are very efficient. The usage of organic farming, integrated pest management (IPM), renewable resources, and promoting biodiversity, including beneficial microbes, natural molecules, and metabolites for maintaining soil health, fertility, and reducing agricultural pest populations. Sustainable agriculture solutions help to reduce the financial burden on farmers and are often cheaper and readily available. Additionally, having minimal negative impacts on the environment and climate change, avoiding issues like soil pollution, water contamination, and harm to crop plants, beneficial natural pollinators, and soil organisms. By shifting toward eco-friendly and renewable approaches, we can protect the earth's natural resources, support agricultural productivity, and ensure food security for future generations. This transformative change is vital for creating a balanced relationship between farming and the environment while promoting economic and social well-being in agricultural commodities worldwide.

Author contributions

Prashant Khare: conceptualized and reviewed the final draft of the manuscript. Manisha Gupta: wrote the manuscript and performed relevant data analysis. All authors have read and agreed to publication.

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