An Insight Into the Consequences of Emerging Contaminants in Soil and Water and Plant Responses

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Chapter 1
An Insight Into the Consequences of Emerging Contaminants in Soil and Water and Plant Responses

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Abstract With the advancement of science, better monitoring of soil and water quality has become possible. Many contaminants have been reported in the recent past that influence the quality of soil and water negatively. However, the consideration of these pollutants or contaminants is still in the initial stage and needs to be explored in detail for a better understanding of their activity as contaminants.

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Emerging contaminants such as agrochemicals, nanomaterials, pharmaceuticals, personal care products, and micro- or nanoplastics have been found to show several harmful impacts on soil or water quality. Emerging contaminants are known to have adverse effects on plants and human beings too. The risk of their entry into the crops, food chain, and any possible interaction to human health should be properly monitored. The concentration of these contaminants in soil and water should also be monitored on a regular basis to avoid the significant damages arising from them. Future study may also be taken into consideration to avoid the possible concerns to natural resources, plants, and human wellbeing.

Keywords Microplastic · Nanomaterials · Pharmaceuticals · Agrochemicals · Personal health care products · Plants

1.1 Introduction

Soil and water are the basic natural resources for agriculture. Soil and water quality plays an important role in deciding farm productivity and agricultural sustainability. Rapid industrialization, urbanization, and increased human population lead to generation of a large volume of wastes which are mostly accumulated in soil/water leading to soil and water contamination. Accumulation of contaminants in soil causes reduction in the productive potential of soil, poor microbial activity, and overall reduction in crop productivity. Knowing about the status of pollutants in soil, their nature, and possible negative impacts is very crucial for understanding the usability of soil and water for particular use. Considering the fact that rising population and rapid urbanization will lead to lesser availability of land and water for agricultural use, it is vital to sustain or improve soil and water quality in all aspects for a healthy growth of crops.

During recent times, an enhanced awareness and concern about the emerging pollutants in soil and water has been noted. Even though their concentration is of very low concentration, they are highly toxic and have significant impact on soil or water quality. Most of the pollutants irrespective of their origin often end up in soil as well as water systems; hence, the risk of soil or water contamination is very high especially in regions with high industrialization. Human activities such as disposal of industrial waste, mining, and excessive and indiscriminate use of agrochemicals in agriculture are few of the contributors to emerging contaminants in soil. Even though the emerging contaminants are highly toxic, very little attention has been given to these emerging contaminants until recent periods (Petousi et al., 2015; Baybil et al., 2022). The risk of entry of these contaminants into the food chain and their possible biomagnification cannot be ignored. In this chapter, an attempt has been made to discuss the major emerging contaminants in soil and water and their adverse impacts on the environment and lifeforms (Fig. 1.1).

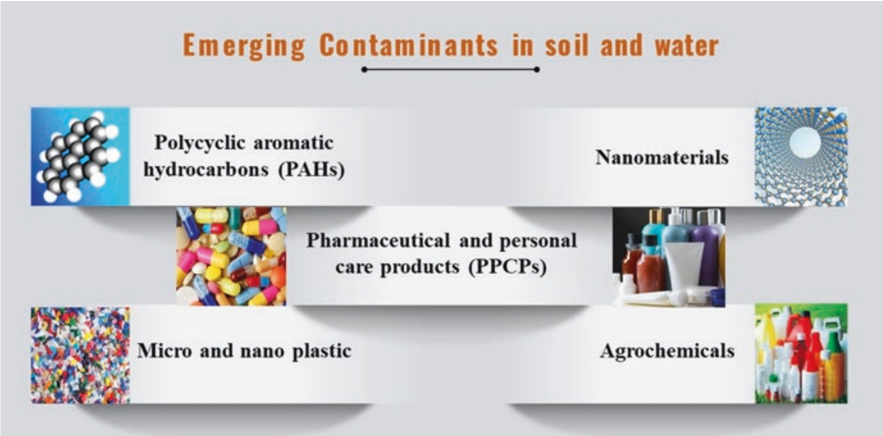

Fig. 1.1 Different types of emerging contaminants in soil and water

1.2 Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds originated naturally in fossil fuels, chemically composed of carbon and hydrogen atoms with benzene rings, colourless or pale yellow coloured, a group of numerous chemically related compounds, and toxic on living organisms (Abdel-Shafy & Mansour, 2016; Drotikova et al., 2021). PAHs are known to suppress immunity and develop mutagenic and carcinogenic effects (Armstrong et al., 2004). In general, PAHs are grouped into three categories, namely, pyrogenic, petrogenic, and biological. In the pyrolysis process, when organic materials are exposed to heat with low or no oxygen conditions, the pyrogenic PAHs are produced. Further, incomplete combustion of motor fuel, forest fire, and burning of cigarettes also produces pyrogenic PAHs (Baklanov et al., 2007). The petrogenic process occurs during crude oil maturation. Biologically PHAs are produced in bacterial and algal synthesis, decomposition of vegetable oil, etc. (Abdel-Shafy & Mansour, 2016). PAHs enter into the environment in several ways. They are found in the air, soil, and water. Like other contaminants, soil PAHs also tend to accumulate in soil. The lipophilic and hydrophobic nature of PAHs makes them persistent resulting in their long-term presence in soil (Li et al., 2019). The persistence of PAHs has also been linked to their number of rings. PAHs with higher rings have been found to be more persistent than PAHs with lower rings (Johnsen et al., 2005). PAHs with a lesser number of rings get solubilized easily in water which make them easily decomposable (Baybil et al., 2022). They have UV absorbance spectra, and each ring has a unique UV spectrum (Abdel-Shafy & Mansour, 2016). PAHs have high melting and boiling points with less solubility in aqueous solution (Masih et al., 2010). Commonly, different PAHs are used in industry in making of colours and dyes, agrochemicals, pharmaceuticals, and plastics, and the use of these products is continuously increasing (Fig. 1.2). PAHs

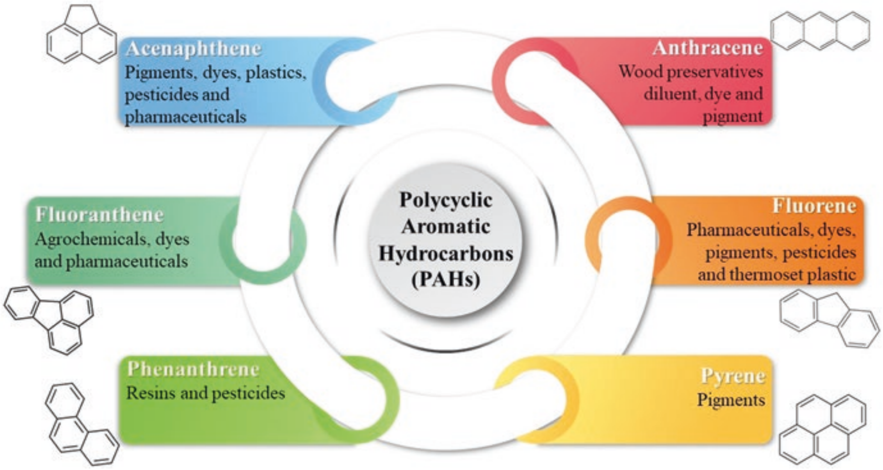

Fig. 1.2 Some common PAHs and the manufactured products

exposed to the atmosphere are deposited to the soil from fuel combustion. Some agricultural inputs such as pesticides and fertilizers may contain PAHs which are applied to the soil, and they become bound to soil particles. The sorption process governs the movement of bound PAH into the soil particle (Abdel-Shafy & Mansour, 2016). PAHs exposed to the atmosphere can be deposited to the natural waterbody, dispersed with the water flow, and settled as sediments (Sany et al., 2012). The PAHs with low molecular weight are soluble and can be dissolved into water.

PAHs show toxicity to aquatic flora and fauna by affecting their metabolic processes. Besides, birds and invertebrates are also adversely affected by PAHs. Mammals including human beings are exposed to PAHs mainly by inhalation, ingestion, and dermal contact (Dong et al., 2012; Veltman et al., 2012; Honda & Suzuki, 2020). Plants absorb PAHs present in the polluted soil, and thus, these enter into the food chain. However, they rarely show phytotoxicity unless concentration is more. The impact of PAHs on human health and plant health has been recorded in the earlier studies (Jameson, 2019; Alkio et al., 2005). The adverse health impact of PAHs on the human body may be acute (ACGIH, 2005; Unwin et al., 2006) and chronic (Diggs et al., 2011; Olsson et al., 2010). Eye irritation, vomiting, skin disease, diarrhoea, nausea, allergy, and confusion are some common health issues that can be caused because of exposure to PAHs. However, reduced immunity, eye disease, jaundice, liver and kidney damage, breathing problems, lung infection, etc., are the chronic health problems. Carcinogenic effect of PAHs has been studied (IARC, 2010). Contrasting results have been reported on the impacts of PAHs on plant growth processes (Baybil et al., 2022). Adverse effects of PAHs are also demonstrated in earlier studies (Alkio et al., 2005; Liu et al., 2009a, b).

PAHs are removed from the environment mainly by biodegradation and photochemical degradation (Sultana et al., 2021). The anaerobic degradation method is adopted in biodegradation (Schraa, 1988). The dissolved or vapour form of PAHs is bioavailable. PAHs sorbet into soil is not easily degraded by microorganisms as PAHs are parted from the enzymes that are used by the bacteria to break them down (Al-Turki, 2009). The PAHs that bonded with soil particles for a longer time show slow desorption. Phenanthrene and chrysene with angular carbon rings are the PAHs that biodegraded faster than others (Wang et al., 2009). The aerobic and anaerobic bacterial species, fungi, extremophiles, archaea, and algae are the bioagents used in microbial degradation (Patel et al., 2020).

Photolysis is another method of degradation wherein the presence of light PAHs stimulates the electrons by making unstable structural arrangements. The structure of PAHs is the determinant of photolysis. Angular structured PAHs degrade slowly; however, photolysis is more effective on the compounds with low molecular weight (Xu et al., 2022). Chemical oxidation is another method of PAH degradation. The effectiveness of chemical oxidation depends on the molecular structure and weight of the compound, oxidizing agents used, and temperature conditions. Titanium oxide and zinc oxide are the catalysts that facilitate UV irradiation of PAHs (Zhang et al., 2008). High-frequency ultrasound is also effective in the degradation process. From the atmosphere also, PAHs are removed by dry deposition (Manariotis et al., 2011) and wet deposition (Wang et al., 2010) methods.

1.3 Nanomaterials

Nanomaterials (NMs) are the materials having particles or constituents of nanoscale dimension, i.e. 1–100 nm (US EPA, 2007), which is produced through nanotechnology. Based on their origin, NMs are broadly categorized into three types such as natural, incidental, and engineered nanomaterials (US EPA, 2008). Most of the NMs that are used in different sectors inclusive of farm inputs are of engineered type and commonly known as engineered nanomaterials (ENMs). ENMs can be made through major three processes such as physical, chemical, and biological (Kolahalam et al., 2019; Baig et al., 2021; Varghese et al., 2019). NMs exhibit special properties which are different from their original forms in terms of physical, chemical, and mechanical strength and electrical conductivity (Bhushan et al., 2014; Lue, 2007; Wu et al., 2020; Saleh, 2020). Properties of soil as well as physicochemical characteristics of ENMs determine the effect of NMs on plants (Nowack et al., 2012). ENMs are widely used in various sectors such as manufacturing of semiconductor, cosmetics industry (Raj et al., 2012; Fytianos et al., 2020), medical imaging (Wen & Steinmetz, 2016), drug delivery (Alizadeh & Salimi, 2021), agricultural input (Peters et al., 2016; Kaphle et al., 2018; Durgude et al., 2022), food sector (Hossain et al., 2021), pollution sensors, and environmental remediation due to their unique properties which make them more efficient. However, environmental impacts and safety standards have been relatively less known.

Manufactured NMs are exposed into the environment through intentional and unintentional releases. They are found in atmospheric emissions, wastes from production facilities, paints, fabrics, agro-inputs, and personal care products (PCPs).

The NMs used eventually mix into the soil and water, and thus they contaminate the valuable natural resources (Ray et al., 2009). Application of biosolids and wastewater is one of the potential sources of addition of nanomaterials in agriculture soils (Pan & Xing, 2012) other than use of nano-inputs to the crop fields, plants, and foods (Hossain et al., 2021; Durgude et al., 2022). NMs are also released to the environment through faulty practices of waste disposal of some products such as cosmetics and electronic devices (Musee, 2011), and ultimately, they are transported to water bodies by runoff (Klaine et al., 2008). The transport of nanoparticles varies largely based on their size, surface chemistry, and various processes in the environment (USEPA, 2010). NMs released to the environment may react with natural materials and remain suspended individually or in aggregate. NMs can persist in air and water as they are in nano-size. The NMs in the porous media become attached to the mineral surfaces (Wiesner et al., 2006). Earlier studies reported that natural NMs that are existing in the nature from the very beginning of the Earth's history (Handy et al., 2008) show a negligible impact on environment and agroecosystem (Rohila et al., 2017); however, the ENMs which are in various use including agricultural inputs can be fatal by causing risks to agroecosystem or humans (Belal & El-Ramady, 2016), and ENMs are of prime importance as emerging contaminants. On the other hand, NMs are used for amelioration of problematic soils and polluted water (Stuart & Compton, 2015; Gil-Díaz et al., 2016). The adverse impacts of NMs are actually the adverse impacts of ENMs into the nature which are narrated in the following paragraphs.

ENMs are applied to the soil and environment for some purposes, and these materials are metal salts (ceramics and nano-silicates); metal oxides (nano-zinc oxide, nano-titanium oxides); nanoparticles of iron, gold, and silver; and carbon nanotubes (Belal & El-Ramady, 2016). Sometimes, unintentional combustion of products may also release NMs to the natural environment (Zhang et al., 2015). NMs are dispersed into the soil and make changes in soil particle aggregates, suspension ability, bioavailability, and transport (de Santiago-Martín et al., 2015). The suspended NMs can alter the physico-chemical properties including ionic strength as well as organic matter content (Delay et al., 2015; Li et al., 2016). They may also develop toxicity (Grillo et al., 2015; Li et al., 2016). NMs may form biofilms by mixing with dissolved organic matter in the presence of root exudates and secretion of microbes (Delay et al., 2015; Hüffer et al., 2018), and the carriage of essential macromolecules is altered (Belal & El-Ramady, 2016). Earlier studies reported that nanoparticles reduced growth of wheat (Dimkpa et al., 2013), nano-ZnO altered transportation mechanism in plants (Lin & Xing, 2008), of nano-Ag registered the cytotoxic and genotoxic impacts (Kumari et al., 2009) and changed the genetic makeup (Prakash et al., 2014; Frazier et al., 2014).

However, NMs are complex in nature, and their interaction in soil is also complex (Pan & Xing, 2012). Therefore, the assessment of risks while applying NMs is to be considered based on the nature and properties of soil and NMs. Soil microorganisms influence the soil biological properties, and they are important in influencing soil fertility and productivity as well as agroecosystem (Maitra et al., 2021). There are several NMs that show anti-microbial properties, and certainly they adversely affect the microbial population (Shah & Belozerova, 2009; Kumari et al., 2014; Van Aken, 2015; Sirbu et al., 2016). In general, NMs have the potential for amelioration or promotion of microbial toxicity (Thul et al., 2013). Based on the studies conducted so far on this aspect, it may be stated that NMs have enough potential to impact on the soil and microbe system and waterbodies; however, further and detailed investigation is needed.

Nanomaterials can pass through the placenta as well as the blood brain barrier owing to their smaller sizes (Liu et al., 2009a, b). Circulatory system of human beings gets affected due to continuous exposure of various nanomaterials (SCENIHR, 2009). The use of sunscreens (which contains mostly nano-TiO_2 and nano-ZnO) exposes the skin to nanomaterials, and these nanomaterials penetrate human skin (Mortensen et al., 2008). Drinking water contaminated with nanomaterials will cause ingestion exposure. Carbon and silica NMs may cause harmful diseases such as pulmonary inflammation, fibrosis, and granulomas, whereas nanoparticles of MnO_2 and TiO_2 adversely affect the brain (Ray et al., 2009).

1.4 Pharmaceutical and Personal Care Products

Pharmaceuticals are therapeutic drugs or medicines that cure and prevent ailments of human and animals, and these are prescribed by registered practitioners (Ebele et al., 2017). However, personal care products (PCPs) are products such as toothpaste, cosmetics, perfume and deodorants, and skincare items (Boxall et al., 2012; Baybil et al., 2022). These two categories of products are collectively known as pharmaceuticals and personal care products (PPCPs) and considered as emerging pollutants of the environment, especially water systems. In the process of manufacture, application, and disposal, the active pharmaceutical ingredients (APIs) are exposed to the environment including river water (Wilkinson et al., 2022) disturbing the aquatic ecosystem. During recent times, the PPCPs have become one of the major threats for human and livestock populations. The European Union (EU) and the US Environmental Protection Agency (USEPA) together listed more than 30 emerging pharmaceutical products exposed to water bodies causing pollution (Ebele et al., 2017). During the period of COVID-19 and afterwards, usage of facemasks has increased, and disposal of used masks further created a worldwide problem. Moreover, PPE kit, surgical face masks, gloves, and gowns are other accessories used in medical treatment having enough potential to pollute the environment (Fig. 1.3). The diversified nature of PPCPs, continuous introduction of new formulation, and increasing use are further adding dimension in this regard.

The conventional procedures of water treatment have some limitations as they cannot remove the physical and chemical properties of PPCPs, and they may persist even in the treated drinking water (Snyder, 2008) imposing the possibility of risks to public health. The pharmaceuticals creating environmental hazards are broadly categorized as persistent and pseudo-persistent (Ebele et al., 2017). The PPCPs when remaining biologically active in waterbodies can influence the normal

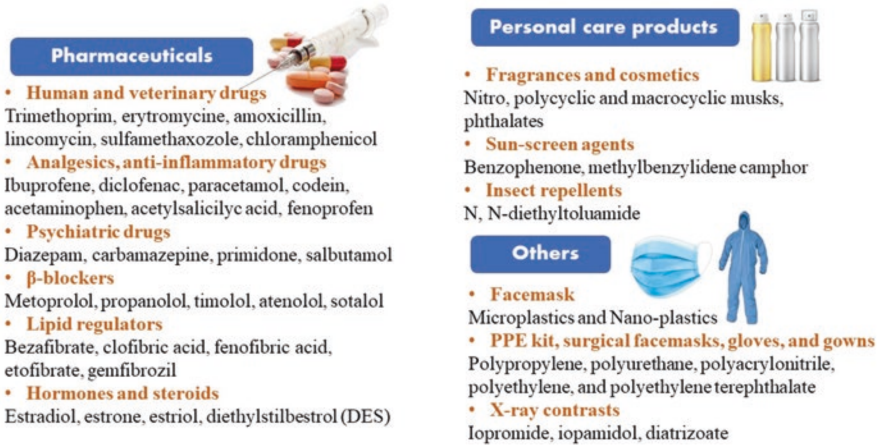

Fig. 1.3 PPCPs as emerging pollutants

biological activities of aquatic animals (Mimeault et al., 2005). The pharmaceuticals containing polychlorinated biphenyls, perfluoroalkyl substances, and polybrominated diphenyl ethers even in low concentration have the potential to alter some metabolic and enzymatic activities of aquatic animals (Fabbri & Franzellitti, 2016). Further, these may influence endocrine activities of aquatic lifeforms causing disruption of homeostasis leading to adverse health impacts. Various sex hormones, veterinary hormones, glucocorticoids, and some other non-hormone pharmaceuticals and PCPs show endocrine disruption (Wielogorska et al., 2015). The endocrine disruptors (EDs) consist of chemicals of natural or synthetic products and various PCPs. Moreover, the mixed form of different EDs with various concentrations can show synergy and fatal effects. The PPCPs are potentially harmful for development of antibiotic-resistant bacterial strains (WHO, 2015). The use of antibiotic is increasing against human and animal diseases, and when a portion of the antibiotic is mixed into the soil and waterbody, it can cause detrimental effect on microbes. It may be caused by development of antibiotic resistance in harmful bacteria and harmful impact on beneficial bacteria in the environment. Additionally, the active ingredients present in PPCP in the waterbody may change their toxicological properties (Isidori et al., 2005). Some acidic medicines when exposed to basic water may exhibit toxicity to non-target organisms (Fent et al., 2006). Actually, the toxicity due to PPCPs greatly depends on the tolerance of the exposed organisms, duration of exposure, and concentration of the harmful ingredient.

The recent addition in this category is mainly because of COVID-19 incidence and post-pandemic situation. This pandemic disease took thousands of lives in the world, and still it is creating problems in a scattered manner in different corners. COVID-19 has taught us to wear face masks and personal protective equipment (PPE) kit. Moreover, surgical accessories such as face masks, hand gloves, and gowns are dispensed after single use as these are non-reusable. They are made up of polypropylene, polyurethane, polyacrylonitrile, polyethylene, and polyethylene terephthalate that take several years to decompose (Fadare & Okoffo, 2020). Globally, 129 billion face masks and 65 billion gloves were used per month during the COVID-19 pandemic (Prata et al., 2020; Zhang et al., 2021). Microplastics and nanoplastics are the materials used in making face mask, causing a threat to the environment. COVID-19 is an infectious disease, and so the used facemasks were not recycled and landfilled (Shirvanimoghaddam et al., 2022); however, proper sterilization prior to landfilling was not followed in many cases. Under environmental conditions, facemasks can undergo different changes because of temperature, UV radiation, or a change in pH (Abbasi et al., 2020) and pollute soil and water. The microplastics can easily enter into the human respiratory system and gastrointestinal tract causing health hazards (Ragusa et al., 2021).

The PPCPs pollute the environment not only in the manufacturing units (Foltz et al., 2014) but also in post-use stages, and they enter the water and soil through different routes (Fig. 1.4). Sewage treatment plants (STPs), wastewater treatment plants (WWTP), and landfill leaching are the most prominent routes (Daughton & Ternes, 1999). The ineffectiveness of traditional wastewater treatment plants in removing these products results in their exposure into the soil and water (Bolong et al., 2009; Cabeza et al., 2012; Baybil et al., 2022).

Incomplete decontamination especially that of pharmaceuticals during treatment process has been attributed as the major reason for accumulation of these emerging contaminants in aquatic bodies where these treated wastewaters are disposed (Cabeza et al., 2012; Baybil et al., 2022; Petrie et al., 2015). Wastewater treatment plants generate huge amounts of sewage sludge (Praharaj et al., 2022; Sagar et al., 2022). Sewage sludge is used in agriculture as it contains various nutrients such as N, K, and Fe (Yang & Toor, 2015). However, application sewage sludge also leads to inadvertent addition of many toxic contaminants into soil. Treated sewage sludge

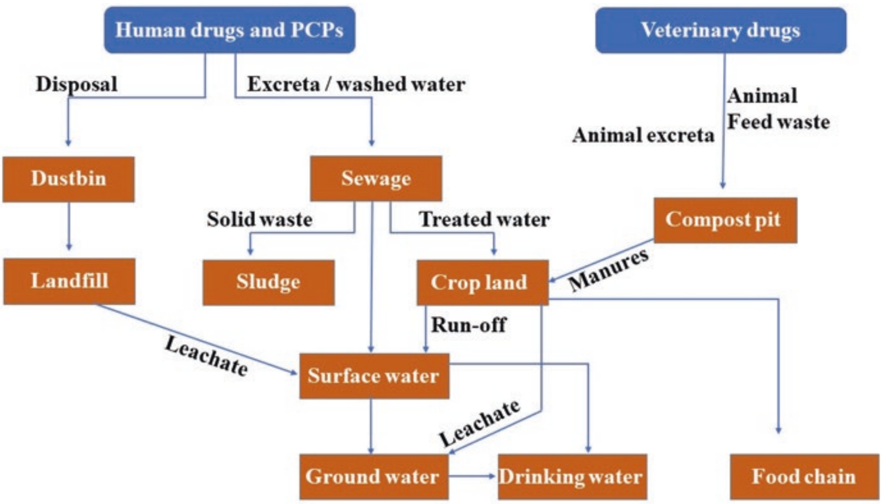

Fig. 1.4 Route of exposure of PPCPs to soil and water

contains many emerging pollutants, namely, antibiotics, chemicals, and ENMs (Koumaki et al., 2021). In addition to sewage sludge, contaminated sources of irrigation water can also add PPCPs into the soil system. Veterinary drugs are exposed to the environment through farm wastes, and these are used in agriculture as manures. The residues of the drugs used for livestock treatment and their metabolites thus enter in the food chain. As the environmental impacts of PPCPs are still not completely understood, they are measured as contaminants of emergent concerns (Vasilachi et al., 2021).

The PPCPs have in general low volatility with high polarity and are hydrophilic in nature, and so, they enter into the environment through aqueous transport and later in the food chain (Caliman & Gavrilescu, 2009; Ebele et al., 2017). The physical and chemical properties of the ingredients of the PPCPs also influence their transport into the environment. The biosolids applied to the crop field and the crops irrigated with wastewater can facilitate entry of pollutants into the food chain (Pedersen et al., 2005). Wastewater treatment plants (WWTPs) cannot totally remove PPCPs (Patel et al., 2019). Further, the leachates and runoff of water from landfill can pollute surface and groundwater (Kleywegt et al., 2007). When PPCPs are released in the environment, degradation and transformation processes start. Solar radiation causes photodegradation. Further, based on the depth of water, season, and composition of the materials, the PPCPs are degraded (Alexy et al., 2004). Microbes present in the environment play a role in the biodegradation process as they take part in wastewater treatment processes (Helbling et al., 2010). Microbes use PPCPs' substrates and increase in number for degradation of the PPCPs. In the wastewater treatment process, the PPCPs are partly or fully destroyed or to some extent transformed to metabolites, and the process largely depends on the composition of PPCPs (Xia et al., 2005).

Increasing application of pharmaceuticals in humans and animals and their subsequent entry into soil and aquatic ecosystems makes them emerging contaminants. Pharmaceuticals may have an ecotoxicological effect on non-target species having the same active sites (Lei et al., 2015). Most pharmaceuticals are present in environments at low concentration that do not cause acute toxic effects. However long-term exposure to such low doses in their lifetime results in significant chronic toxic effects (Lei et al., 2015). The veterinary drugs used for animals are also released into the surrounding in bioactive form through excretion which may result in long-term adverse effects on soil, water, animals, plants, etc., and these may also adversely affect human health through food chain contamination.

1.5 Micro- and Nanoplastics

Microplastics and nanoplastics are considered as emerging pollutants which are to be recognized as emerging threats (Liu et al., 2021). Microplastics are plastic substances of 0.1 μm to 5 mm in size, while size of nanoplastics ranges between 0.001 and 0.1 μm (Caputo et al., 2021). Microplastics are found in the environment in the form of fragments, granules, fibres, and spheres or microbeads (Velimirovic et al., 2021), while the shape of nanoplastics in the environment is still unknown because of methodological complications involved in their detection and characterization. Fragments of these micro- as well as nanoplastics are so small that they are neither visible to naked eye nor under a simple optical microscope.

Microplastics and nanoplastics are added to the soil through natural as well as anthropogenic activities. Natural processes include atmospheric inputs (Allen et al., 2019) and flooding with lake and river water (Horton et al., 2017). Various agricultural practices, namely, polyethylene mulching, irrigation with plastic polluted waste water, application of soil amendments containing plastics, and illegal waste dumping are the major anthropogenic activities which introduce micro- and nanoplastics to the soil (Sarkar et al., 2022; Ng et al., 2018).

Microplastics are further broadly grouped as primary and secondary microplastics (Duis & Coors, 2016). Primary microplastics are directly formed from resins and pellets which are utilized in the plastic industry or plastic exfoliating products such as body and face scrubs. On the other hand, secondary microplastics are formed by the fragmentation and weathering process of larger size plastic materials (Lambert & Wagner, 2016).

Various weather parameters such as ultraviolet radiation, alternate wetting and drying periods, and oxidation reduction reactions help in fragmentation of plastic materials. Anthropogenic factors, e.g. mechanical action by machineries during tillage, result in production of microplastics as well as nanoplastics, and their size depends on thickness of layer and heterogeneity with respect to surface of the plastic material. During the fragmentation and disintegration process of formation of microplastics and nanoplastics, there is mechanical alteration. As a result of which, various chemical groups are exposed and bind to exogenous chemicals impacting the plastic degradation rate (Fotopoulou & Karapanagioti, 2012, 2019).

The behaviour of plastics in the soil mainly varies based on their physical properties even though they differ in chemical composition. Crystalline structure in fact is one of the main factors influencing the reactivity of plastics. Plastics having low values of crystalline-to-amorphous ratio are more reactive compared to those having higher values. Higher pore surface and adsorption of chemicals of plastics having low values of crystalline-to-amorphous ratio make them more susceptible to degradation and formation of micro- and nanoplastics. Nanoplastics are chemically more reactive and mobile than microplastics due to higher specific surface area (Hu et al., 2019; Gigault et al., 2018).

Plastics are rapidly colonized by microbes mainly bacteria and form biofilms commonly known as bacterial biofilms (Zettler et al., 2013), and these bacterial biofilms increase chemical adsorption by microplastics (Fotopoulou & Karapanagioti, 2019). Size of nanoplastics is even smaller than most bacteria and viruses, and therefore, no biofilm is seen in the case of nanoplastics. However, pathogens get associated with nanoplastics.

Mostly in the case of microplastics, the major risk associated is they get stuck in the guts of living organisms. However, due to very small size of nanoplastics (i.e. less than 50 nm), they penetrate both prokaryotic and eukaryotic cell membranes with absorbance of pathogenic microbes, thus increasing the biohazard potential of the pathogens. As both microplastics and nanoplastics transport pathogens and chemicals in a passive manner, they are known to show the so-called Trojan horse effect (Zettler et al., 2013; Galloway et al., 2017; McCormick et al., 2014). This Trojan horse effect of micro- and nanoplastics is associated with potential and neglected health hazards for human beings. Microplastics and nanoplastics contaminate the soil and alter physical, chemical, and biological properties of the soil (Pathan et al., 2020; Rillig et al., 2017; Kasirajan & Ngouajio, 2013).

1.6 Agrochemicals

Agrochemicals are the synthetic chemical substances that are being used in agricultural production. Agrochemicals mainly consist of two broad groups, i.e. synthetic fertilizers and pesticides. Most of the fertilizers used in agriculture are inorganic chemicals (except urea), while pesticides are organic in nature. Insecticides, herbicides, fungicides, bactericides, acaricides, etc., are broad categories of pesticides being used to control respective pests. Based on the chemical structure, pesticides are further classified into organo-phosphorous, phenols, phenolics, organochlorines, metallo-organics, nitrogen benzenes, etc. Modernization of agriculture resulted in increased use of both fertilizers and pesticides. However, non-judicious and imbalanced use of these chemical substances has emerged as a potential soil and water contaminant.

Today, on a worldwide basis, there are approximately 1000 pesticides consisting of 800 active ingredients in use, and the number is still increasing (Zhang et al., 2019). Only 1% of applied pesticides is used for pest control that means it reaches the target site of the pest, and the remaining portion accumulates in surrounding soil, water, and air and ultimately enters food chain and affects various non-target species including human beings (Lozowicka et al., 2016; Rani, 2015). Around 80–90% of the applied pesticides to agricultural crop fields contaminate soil, water, air, and non-target plants either directly or indirectly through the process of runoff and drift from on-site pesticide accumulation. Half of this 80–90% of chemical residues are further converted through microbial or chemical processes (known as transformation products) which persist in the ecosystem for more than 10 years.

The adverse impacts of indiscriminate use of these agrochemicals have resulted in reduction in soil fertility, inhibition of growth of beneficial soil microorganisms (Feld et al., 2015), increased concentration of heavy metal, reduction in quality of groundwater, etc. (Ali et al., 2016), and all these ultimately cause reduction in agricultural crop production.

Herbicides above their recommended dose of application affect growth and behaviour of microorganisms having an influence in change in nutrient dynamics in the soil (Das et al., 2015). Various pre-emergence herbicides, e.g. prodiamine, indaziflam, and isoxaben, reduced the accumulation of various macro- (phosphorus, potassium, sulphur, magnesium) and micronutrients (zinc) in affected plants.

The Stockholm Convention has classified some of the pesticides as persistent organic pollutants, i.e. known as POPs (Stockholm Convention, 2021). These POPs are highly persistent in soil and capable of long-distance transport and adversely impact human health and environment. Chlorinated organic compounds such as DDT, dieldrin, aldrin, endrin, chlordane, toxaphene, heptachlor, endosulfan, and hexachlorobenzene are some of the pesticides which are being classified as POPs by the Stockholm Convention. Pesticides belonging to organophosphorus class are the most frequently found pesticides in contaminated soils and have potential risk to humans as well as wildlife (Ballestas et al., 2016). Because of longer persistence of organochlorine pesticides, they are still detected in soil and water despite being banned for use (He, 2017). The most common causes of pesticide poisoning in the world are carbamates and organophosphates (Huang et al., 2015; Lim et al., 2015).

1.7 Interaction Between Emerging Contaminants and Plants

Based on prime concerns related to health and environmental issues, several nations expressed their concerns on emerging contaminants; however, these pollutants when exposed to the environment cause adverse effects not only to health of humans but also that of plants (Santos et al., 2012). Soil contamination is caused by mining, industrial effluents, chemical farm inputs, and unscientific waste disposal by which plants are directly influenced. Further, penetrating impacts of soil and water pollution by emerging contaminants are presumed to reduce crop productivity by altering the physiological and metabolic activities of the plants, and thus, they can cause loss of arable land and habitats of plants (Santos et al., 2012). Crop plants raised under pharmaceutical-contaminated soil uptake the pollutants and can convert them into more toxic substances through drug-metabolizing enzymes. Pharmaceuticals are potentially harmful to plants as they modify enzyme functioning in plants and alter the physiological activities of the plants (Zrncic et al., 2014; Navratilova et al., 2021; Podlipná, 2022). The reactive and hydrophilic compounds as pharmaceutical pollutants make xenobiotic metabolism in plants more complicated where these react with glutathione, glucose, and amino acids and can produce more toxic compounds, and consumption of the contaminated plants by invertebrates or other animals can be fatal (Wagil et al., 2015; Podlipná, 2022). Organic manures derived from animal wastes are one of the important sources of nutrients to plants, and the organic manures may consist of animal excreta and livestock farm wastes. A portion of the drugs used in animal farms remains in the livestock excreta, and the converted organic manure may also contain the same. The anthelmintics drugs such as thiabendazole, albendazole, mebendazole, flubendazole, fenbendazole, and triclabendazole commonly used for deworming of livestock can be exposed to the environment through the manures and liquid form of animal excreta and could have adverse impacts on plants. Fenbendazole and its metabolites are known to alter the protein and gene expression in *Arabidopsis thaliana* inclusive of other physiological and metabolic processes (Syslova et al., 2019). The physiology and metabolism of soybean are also influenced by anthelmintics drugs (Podlipna et al., 2021).

Pesticides used in agriculture to control insect-pests, diseases, and weeds have harmful influences on soil and environment as residues, and they are absorbed by the plants when exposed. To safeguard the human beings from the toxic effect of pesticide residues in the agricultural crops, the World Health Organization (WHO) developed internationally accepted maximum residue limits (WHO, 2022). The common symptoms of pesticide toxicity to plants are necrosis, chlorosis, burns, and deformation of leaves (Sharma et al., 2019). The sensitive plants are more vulnerable to pesticide toxicity. The oxidative stress caused by pesticides toxicity may result in chlorophyll degradation, protein synthesis, and other metabolic activities (Badr et al., 2013; Kilic et al., 2015; Jiang et al., 2016). Moreover, Shahid et al. (2021) mentioned that agrochemical residues acted both positively and negatively on crop plants. A study mentioned that there was no change in nitrogen and protein content in chickpea grain due to pesticides (Khan et al., 2009). The residue of some herbicides such as pendimethalin, atrazine, and alachlor in soil adversely affected germination of crop seeds (Rajashekar & Murthy, 2012; Moore & Kröger, 2010; Tanveer et al., 2009). Further, reduced plant growth was reported due to presence of herbicide residue in the soil (Nadasy et al., 2000). Herbicides are known to disturb nitrogen metabolism and photosynthesis (Nadasy et al., 2000). Fipronil, an insecticide, reduced seed germination in rice; however, diazinon enhanced it (Rajashekar & Murthy, 2012). Dimethoate also negatively impacted on the physiological processes of crops, namely, disturbance and electron transport chain in photosystem II, and reduced assimilate production (Mishra et al., 2008; Shahid et al., 2021). Chibu et al. (2002) reported that application of pesticide chlorpyriphos increased growth and yield attributes and crop productivity in rice and soybean. Similarly, beneficial effects of insecticides application were recorded by Glover-Amengor and Tetteh (2008) in tomato. The fungicide triazole is known to restrict electrolyte leakage and lipid peroxidation in carrot (Gopi et al., 2007). A study revealed that another fungicide named azoxystrobin boosted superoxide dismutase and catalase-peroxidase activities (Wu & Von Tiedemann, 2002).

Micro- and nanoplastics exposed to the environment interact with the plants. Several studies revealed that they reduced chlorophyll content in the plants such as wheat, maize, grass pea, and others (Lian et al., 2020; Wang et al., 2021; Li et al., 2020). Biochemical activities of plants were also influenced by micro- and nanoplastics where peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT) enzyme activities were boosted and along with malondialdehyde (MDA) content (Azeem et al., 2022). In the case of photosynthesis, different types of impacts (neutral, beneficial, and harmful) were noted (Boots et al., 2019; Lian et al., 2021; Zeb et al., 2021) based on the exposed times. The smaller particles of micro- and nanoplastics remained more harmful (Lee et al., 2013).

ENMs are used in agriculture for various purposes such as pest management as new pesticide formulation, identity preservation, sensors to monitor soil conditions, hydrophilic and hydrophobic materials for water conservation, supply of plant nutrients and agrochemical delivery, and genetic engineering purposes (Aslani et al., 2014). Researchers recorded beneficial, harmful, and inconsequential impacts of ENMs to plants (Muller et al., 2005; Bystrzejewska-Piotrowska et al., 2009; Sohaebuddin et al., 2010). However, there is enough evidence which indicates phytotoxicity also (Aslani et al., 2014). Carbon nanotubes (CNTs) were observed to increase seeding growth in rice (Smirnova et al., 2012), but Al_2O_3 NMs reduced root growth of cucumber, maize, carrot, soybean, and cabbages (Kollmeier et al., 2000; Yamamoto et al., 2001; Tian et al., 2007), while ZnO NMs caused toxicity (Ma et al., 2009; Srivastava et al., 2021). The phytotoxicity was related to particle size and surface area (Aslani et al., 2014), and an enhanced surface area determined the number of reactive groups on the surface (Begum et al., 2011). A positive impact of ENMs such as multiwall CNT, Zn, and ZnO was recorded in favouring germination and seedling vigour of Indian mustard and black gram (Ghodake et al., 2010). In conformity, another study revealed that ZnO impacted adversely on seedling germination and plant growth processes (Sharma et al., 2009). Au ENMs also show phytotoxicity (Bai et al., 2010). Actually, the present phytotoxicity profile of ENMs is speculative, and hence, further research is to be intensified into the direction.

1.8 Future Scope of Study on Emerging Contaminant

1. The persistence and bioavailability of different emerging contaminants needs to be studied thoroughly. Their chemical characterization and its relation to persistence need to be evaluated. Persistence of different emerging contaminants under different environments also needs to be evaluated.
2. The risk of different emerging contaminants on human health should be studied. The risk of entry of emerging contaminants into the food chain and the risk of biomagnification need to be evaluated. Food safety regulation in this regard can be made.
3. The existing waste water treatment system needs to be improved to remove the emerging contaminants effectively. This can help in eliminating the entry of emerging contaminants to soil or aquatic systems and thus save the plants from toxicity.
4. Guidelines should be developed to largely avoid or exclude the use of any such ingredients in personal care products that serve as a potential threat to the environment. The ecotoxicity of ingredients should be taken into consideration while developing personal care products.
5. Regular monitoring of emerging contaminants in soil and aquatic systems should be done. Care must be taken to avoid the buildup of these contaminants.
6. Interaction of the emerging contaminants with soil components, i.e. organic matter, mineral components, and soil moisture, should be studied. As persistence and bioavailability are usually affected by these components, hence it will be interesting to know how the emerging contaminants are behaving in relation to interaction with these components.

7. There is a need for thorough study on the mechanisms of micro- and nanoplastics, engineered nanomaterials, and other emerging contaminants by using transcriptomic, proteomic, and metabolomic tools, and the study will help to understand the dynamics of plant responses and resilience.

1.9 Conclusion

Limited availability of productive land and increasing pressure of feeding an ever-growing population make it even more important to take care of the soil resource. Rising population, changing lifestyle, rapid industrialization and urbanization, unsustainable production and value chain management system, etc., are few of the factors that have led to production of huge amounts of waste and contaminants which are accumulated in soil. Many of these contaminants have only been recently studied, and still a lot needs to be researched upon these contaminants to properly understand their environmental impact. Such emerging contaminants when properly characterized and studied for their potential risks can be properly managed. An integrated management strategy that both avoids the production of these contaminants at source and minimizes the impact of the contaminants in soil can help in minimizing the risks arising from these contaminants.

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