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A systematic review of emerging pollutants: general impact on the ecosystem

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ABSTRACT

Industrialization in Nigeria has resulted in the production of diverse products by various industries engaged in the production of goods. The effluents from these industries are the most probable sources of emerging contaminants in the Nigerian environment. The occurrence of these contaminants of emerging concern (CECs) in several environmental compartments has raised significant concern given the extensive array of compounds and their consistent detection across various environmental matrices. However, providing data on their occurrence is crucial and lays the groundwork for decision makers to craft mitigation strategies toward a more sustainable water policy. Hence, this study therfore aims to bring out the importance of EPs, explore their mechanisms of persistence and assess the ecological, human, and socio-economic risks associated with their presence in the environment. The discussion begins with a detailed definition of emerging pollutants and their distinguishing characteristics. Emphasizing their sources, pathways, and environmental behaviors. The focus then shifts to environmental impacts on socio-economy, wildlife, ecosystem and humanhealth.

1. Introduction

Industrial Industrialization brought about significant changes in pollution patterns, introducing new contaminants into the environment (Wang, Walker, Muir, 2020) and has basins have become a significant threat to coastal and estuarine ecosystems (Thompson, 2018). Anthropogenic activities have also resulted in increasing pollution load in various environmental compartments within the coastal ecosystem. With the onset of the anthropocene, humans have increasingly depleted natural resources and developed new chemical molecules in pursuit of global development, resulting in waste streams transgressing planetary boundaries, disrupting natural ecosystems (Matlin, Cornell and Krief, 2022; Steffen, Richardson and Rockström, 2015). Because of their rapidly increasing use in industry, transport, agriculture, and urbanization, these chemicals are entering the environment at increasing levels as hazardous wastes and nonbiodegradable substances (Gavrilescu, Demnerová, Aamand, Agathos and Fava, 2015). Until the beginning of the 1990' non-polar hazardous compounds like persistent organic pollutants (POP) and heavy metals, were in the focus of interest and awareness as priority pollutants. Today, the emission of "emerging" contaminants has emerged as an environmental problem (Petrovic, Sabater, Elosegi and Barceló, 2016). The adverse effects caused by these contaminants are of current interest to many researchers across the globe to ensure environmental sustainability (Mani, Pachaiappan, Gowda and Aroulmoji, 2023).

1.2 Emerging Contaminants

Emerging pollutants (EPs)otherwise called emerging contaminants (EC) refer to a diverse group of chemical and biological substances that are not commonly monitored in the environment, but have the potential to cause significant ecological and human health impacts (Vasilachi, Asiminicesei, Fertu and Gavrilescu 2021); and the potential risks they pose to human health **(**Sahu and Sahu, 2020). The "emergence" of the awareness of emerging contaminants should probably be attributed to Rachel Carson for her 1962 book "Silent Spring". She convincingly showed that the widespread usage of DDT to eliminate mosquitoes and other pests had led to the death and disappearance of many birds (Lutz, Bai, Carroll and Keteles, 2018). According to Krishnakumar, Singh, Godson and Thanga (2022), emerging pollutants (EPs) are chemicals and compounds that have recently been identified as dangerous to the envi ronment and ecosystems, including the health of human beings (Krishnakumar *et al.*, 2022). They are labeled as "emerging" not because they are newly introduced into the environment but due to the growing recognition of their presence and potential hazards facilitated by advances in analytical detection techniques (Feng, Huang and Chen, 2021; Senthil, Senthil and Vo, 2021; Kumar *et al.*, 2023; Mali *et al.*, 2023). Advances in analytical techniques have led to the increased detection of these substances in diverse environmental matrices, raising concerns about their potential to disrupt ecosystems and threaten human health (Metcalfe, 2013; Vasilachi *et al.*, 2021). The globalization of trade and the widespread use of various chemicals have facilitated the global distribution of ECs, which are found not only in industrialized areas but also in remote regions. Additionally, the interaction between different ECs can result in synergistic effects, complicating assessing and managing their associated risks (Li, Shen, Jiang, Xi and Li, 2024, Tong *et al*., 2022).

Many of these compounds resist natural attenuation processes such as biodegradation, photodegradation, and chemical transformation, allowing them to accumulate in ecosystems and persist over long timeframes. Furthermore, these ECs have the potential to undergo additional transformation and long-range transport, creating unforeseen and uncharacterized chemicals and causing chemical pollution in areas distant from the source (Machado, Grassi and Vidal, 2016).Their mobility further exacerbates the issue, as EPs can be transported over long distances via water currents, atmospheric deposition, and biological pathways, making them a transboundary concern (Shaheen, Sizirici and Yildiz, 2022; Tong *et al*., 2022).

1.3 Classes of Emerging Contaminants

ECs encompass many substances detected in the environment but are not commonly monitored or regulated. These pollutants include a variety of compounds such as antibiotics, drugs, steroids, endocrine disruptors, hormones, industrial additives, chemicals, and also microbeads and microplastics (Krishnakumar, Singh, Godson and Thanga, 2022; Sousa, Ribeiro, Barbosa, Pereira and Silva 2018). These contaminants can be classified into several categories based on their origin, use, and chemical characteristics. They are composed of products used in large quantities in everyday life and encompass a wide range of pharmaceuticals, personal care products (PPCPs), industrial chemicals, pesticides, nanomaterials, and microplastics, many of which have not been fully regulated or systematically monitored (Paiu, Favier and Gavrilescu, 2024; (Luo *et al.*, 2024; Sahu and Sahu, 2020; Thomaidi, Matsoukas and Stasinakis, 2017). surfactants and surfactants' residues, plasticizers and different industrial additives. The global population growth, fueled by industrialization and urbanization, has spurred increased demand for them. Consequently, industries producing these goods, such as pharmaceuticals, household products, and plastics, have expanded significantly (Johnson and Bell, 2022).

1.3.1 Pharmaceutical and personal care products – illicit drugs

Pharmaceuticals and personal care products (PPCPs) are a broad category of chemical substances encompassing many compounds, including prescription and over-the-counter drugs and personal care products such as fragrances, lotions, and cosmetics. These substances are antidepressants, birth control medications, pain relievers, sunscreens, and fragrances commonly used in daily life for various purposes, including human and animal healthcare. Among these biologically active substances, antibiotics have emerged as the most commonly reported PPCPs over the past few decades (**Berglund, Ebmeyer and Kristiansson, 2023**; Browne, Chipeta and Haines-Woodhouse, 2021; Manai, Aga and Cytryn, 2024). Most PPCPs have the tendency to persist or to be only partially degraded during treatment or even to bypass treatment (Arguello-Pérez, Mendoza-Pérez and Tintos-Gómez, 2019; Ebele and Abdullahi, 2017; Jury, Khan, Vancov, Stuetz and Ashbolt, 2011). After production and application, PPCPs are primarily introduced to the environment directly or indirectly through the discharge of raw sewage or treated effluents of various quality from wastewater treatment, animal husbandry, animal manure, or municipal treatment plant sludge as fertilizer, and landfill leachate (Carpenter and Helbling, 2018; Carpenter, Wong and Johnson 2019; Hu, Li and Zhang, 2023). These compounds can enter the environ ment through various pathways, such as improper disposal, wastewater treatment plant effluents, and agricultural runoff, and their potential impacts on ecosystems and human health are an active area of research and regulatory attention (Wang et al., 2023a). The distribution of these compounds in water raises concerns about their impact on aquatic ecosystems (Lee and White, 2016**;** Sahuand Sahu, 2020).

Pharmaceuticals are a significant class of emerging contaminants, often originating from the disposal of unused medications and excretion into sewage systems (Smith and Brown, 2015). As the main components of PPCPs , they include numerous types of illicit drugs and their metabolites, hormones, non-steroidal anti-inflammatory drugs, anticancer drugs, antiepileptics, antidepressants, and β-blockers(Wilkinson, Boxall and Kolpin, 2022; Manaia *et al.*, 2024). Personal care products, unlike pharmaceuticals, are applied externally and hence do not undergo any metabolic changes prior to their release to the aquatic environment. They include cosmetics and toiletries, mosquito repellants, antimicrobial and antifungal agents, surfactants, perfumes and sunscreens which are widely used and form a permanent feature of urban lifestyles. Products like shampoo, conditioner and bar soap easily wash off into septic storage tanks when a shower is taken or are sent directly to a wastewater treatment plant. These compounds have been widely detected in aquatic environments and can accumulate in wildlife, potentially posing ecological risks (Lee and White, 2016; Sahu and Sahu, 2020).

1.3.2 Pesticides

Pesticides, widely used in agriculture, forestry, horticulture and for residential purposes, contribute to chemical contamination. They are commonly associated with agricultural runoff, contaminated soil, and water sources (Green and Davis, 2017). When applied to crops for their protection against different pests and diseases, pesticides eventually reach the soil by being washed by rain or by spray drift. From the soil, the pesticides drift to aquatic environments including ground waters and surface waters (Moreno-González, Campillo, García and León, 2013). Studies have shown that pesticide metabolites are often detected in groundwater at higher concentrations compared to parent compounds from both agricultural and amenity use (Bai, Lutz, Carroll, and Keteles, 2018). Research has indicated links between pesticide exposure and various human health risks, emphasizing the importance of pesticide regulation (Green and Davis, 2017; Sahu and Sahu, 2020).

1.3.3 Industrial additives and by-products

Industrial compounds are not necessary emerging contaminants but they are classed as priority pollutants. However, some of their breakdown products may be regarded as emerging contaminants (Moreno-González, *et al.*, 2013). The improper disposal of organic solvents and pesticides can contribute to the accumulation of toxic compounds in the environment, potentially disrupting natural cycles and impacting the food chain (Li *et al.,* 2024). These are toxic and persist in the environment. These substances, often produced due to various industrial processes, can pose a significant threat to the envi ronment and human health if not properly managed (Sorvari and Wahlstrom, 2024).

1.3.4 Flame/fire retardants

These are flame retardants like polybrominated diphenyl ethers (PBDEs) and are another group of ECs indispensible to the environment as they are widely used in thermostats, textiles, thermoplastics, coatings in furniture, foam, plastics and electronics to prevent the spread of fire. Polybrominated diphenyl ether flame retardants are extensively used in resins for household and industrial use and may enter the environment via waste disposal to landfill and incineration. These compounds exist at higher concentrations in sediments more than in surface waters because of their hydrophobic nature. However, they can easily be transported long distances away from their source of release and studies have shown that they are in regular presence in human and animal tissues, blood and milk (Ela 2011; Cantwell *et al.*, 2018).

1.3.5 Surfactants (Perfluorinated sulfonates and carboxylic acids)

Perfluorinated sulfonates and carboxylic acids including perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) and Alkylphenolethoxylates (APEOs) have been used for over 50 years in food packaging and cookware coatings, paints and surfactants cosmetics and fire-fighting foams with consequent entry to the environment by run-off from sites of major fires. Alkylphenolethoxylates (APEOs) are non-ionic surfactants widely used in the formulation of a large variety of detergents, paints, resins, pesticides and lubricants. Alkylphenols are biotransformation products of their corresponding APEOs. Perfluorooctanesulfonate (PFOS), perfluorooctanoic acid (PFOA), and their salts are the most essential and are widely used in fire-fighting foams, lubricants, metal spray plating and detergent products, inks, varnishes, coating formulations, waxes, water and oil repellents for leather, paper, and textiles (Arvaniti and Stasinakis, 2015). PFCs exhibit high heat, light, and chemical stability, and they are not easily degraded by microbial metabolism (Miralles-Marco and Harrad, 2015). PFCs are therefore regarded as persistent, bioaccumulative and potentially hazardous to animals and humans.

1.3.6 X-ray contrast media

According to Florence Doo, Iodinated X-ray contrast media (ICM) as emerging micropollutants have attracted considerable attention in recent years due to their high detected concentration in water systems. “Iodine and gadolinium are nonrenewable resources that can enter wastewater and accumulate in rivers, oceans, and even drinking water," explained lead author Florence Doo, MD, MA, Director of Innovation and Assistant Professor at the University of Maryland Medical Intelligent Imaging Center (UM2ii) in the Department of Diagnostic Radiology and Nuclear Medicine, and Faculty at the University of Maryland Institute for Health Computing (Zhang, Fourcade, Amrane and Geneste, 2023). The X-ray contrast media are injected intravascularly at high doses to enhance the contrast of X-ray images of organs and blood vessels. They are metabolically stable and usually excreted within a day of in-take. The contrast media detected in urban waters include iopamidol, iopromide and iohexol, which are very persistent and polar in nature. Research has shown that the removal of iodinated X-ray contrast media (ICM) in conventional biological wastewater treatment is limited. These ICMs have been found to occur in surface waters and ground waters at µg/l concentrations (Pérez and Barceló, 2007).

These nonrenewable resources can enter wastewater and accumulate in rivers, oceans, and drinking water, posing risks to aquatic ecosystems and public health (Zhang *et al.*, 2023). In addition, ICM has an average half-life in the human body of around 2 h, and 75% of the administered dose is excreted via urine or feaces into the hospital wastewater within 4h and nearly 100% within 24 h (Li *et al.*, 2020). They were identified as a major source of increased absorbable organic halogen (AOX) concentrations in hospital sewage water (Nowak, Pacek and Mrozik, 2020). In a large part of the region, hospital wastewater is not treated separately and is finally discharged into the local sewage systems together with domestic wastewater (Barge, Baricco, Cravotto, Fretta and Lattuada, 2020)

1.3.7 Plasticizers (Endocrine disrupting chemicals - EDCs)

Plasticizers comprise alkylesters, naphthalene, bisphenol A (BPA), dioxins, perchlorate, polychlorinated bi phenyls (PCBs), and alkylphenols, found in plastics, sulfonates and a variety of other compounds that are added to materials such as plastics, concrete, clays, and gypsum to improve plasticity. Some plasticizers are potential endocrine disruptors (BPA). EDCs are a class of compounds that can interfere with the normal functioning of the endocrine system. They normally mimic, block or disrupt the action of natural hormones; and these lead to adverse effects on the growth, development, reproduction and other vital functions. The accumulation of EDCs in aquatic ecosystems poses a growing threat to wildlife and human health (Kurowska *et al*., 2022). Exposure to EDCs can occur through various sources, including food, water, consumer products and the environment (Aydemir and Ulusu, 2023). BPA enters the water cycle through several different pathways including plastic manufacturing plants during the natural breakdown of plastics, exhaust from domestic waste incinerators; leachates from landfills and discharge of WWTP effluents (USEPA, 2010). Research has shown that EDCs are linked to various human health issues and can cause reproductive and developmental problems in wildlife (Reincke *et al.,* 2024). It has also been shown to affect adipokines and reproductive functions and disrupt normal biological processes.

1.3.8 Fluorescent whitening agents (FWAs)

Fluorescent whitening agents (FWAs) are a class of fluorescent dyes capable of absorbing ultraviolet light (wavelength 300–400 nm). They are highly conjugated fluorescent compounds that are added to textiles, laundry detergents, and paper and plastic products, mostly to enhance white color. This fluorescence complements the yellow light reflected by the substrate, thereby significantly enhancing the whiteness and brightness of materials (Wu *et al.,* 2021; Guo *et al.,* 2024). According to Niloy, Haque and Tareq (2021) fluorescence whitening agents (FWAs), popular optical brighteners, are extensively used in commercial detergents to increase brightening of washed products (Niloy, Haque. and Tareq, 2021). Many FWAs are relatively water-soluble, non-biodegradable and therefore, used as markers for wastewater in surface waters. FWAs are widely used in industries such as detergents, textiles, printing and dyeing, plastics, papermaking, and coatings as a result of the enhancement (Blanc *et al.,* 2020; Niu *et al.,* 2016). FWA enter surface waters via wastewater discharges. Fluorescent Whitening Agent (FWA) could also be considered as harmful as it has more negative impacts on environment. Inspite of being hydrophilic, FWAs are persistent in nature and could not completely be removed from aquatic environments (Salas *et al*., 2019; Niloy, Haque. and Tareq, 2021). Firstly, in contrast to other detergent components, FWAs are known to be very poorly degradable (Salas *et al*., 2019). Secondly, FWAs are not carcinogenic itself, but when they occur together with ultraviolet radiation at certain wavelengths, a pronounced carcinogenic effect may result due to photochemical transformation (Falk and Bingham, 1973). With the presence of UV radiation, structure of FWA changes and turns into a format to cause possible carcinogenic effects in human body as well as other living species. Aquatic species (fishes, bacteria, yeasts) could be the sufferer due to toxicity mainly caused by large scale of detergent usage and poor degradation and persistent nature of FWA in surface water. Possible other health problems could be eczema, allergies, skin infections and in some cases, cancer as detergent may contain carcinogens (Niloy, Haque. and Tareq, 2021).

1.3.9 Artificial sweeteners

The growing consumption of synthetically manufactured sugar substitutes, coupled with the lack of adequate national and international regulations, has led to the presence of various compounds, in different environmental matrices. The consumption of artificial sweeteners has become a lifestyle habit as these are low calorie products. High-intensity artificial sweeteners, synthetically manufactured sugar substitutes, were introduced to the market in 1983 and their production and consumption have continued to increase. The most widely used sweeteners worldwide are acesulfame-k, aspartame, cyclamate, neotame, saccharin, and sucralose, which are mainly used in beverages and foods (Sang, Jiang, Tsoi and Leung, 2014; Fernandez, *et al*., 2025). Their use is aimed at reducing calorie intake in people with diabetes, athletes, and those seeking to control their weight (Bowen, Denny, Zahedi and Bidaisee, 2018; Naidu, Espana, Liu and Jit, 2016). These are also used in food and beverages, desserts, chewing gums, pastries and breads especially for diabetic and/or obese people and other personal care and pharmaceutical products (Naik, Zafar and Shrivastav, 2018) such as toothpastes and cough syrups. Because of the high consumption of artificial sweeteners, coupled with their low absorption rate in the human body, they are released into wastewater. As it stands today,sucralose and other artificial sweeteners have recently been identified as persistent emerging pollutants (Richardson and Ternes, 2011).

Around 98% of the sucralose consumed by humans is excreted without undergoing any change; it can be very persistent in the aquatic environment (Loos *et al.*, 2009). Because of their recalcitrance to transformation, acesulfame and sucralose were viewed as an ideal marker for the detection of domestic wastewater in environmental waters, particularly groundwater (Oppenheimer, Eaton, Badruzzaman, Haghani and Jacangelo, 2011). These compounds, which have been introduced into the environment for several years, have acquired the status of emerging contaminants as their detection in the environment has only been possible thanks to advances in highly sensitive analytical techniques (Fernandez, Colás-Ruiz, Bolívar-Anillo, Anfuso and Hampel, 2021; Roberts, 2016; Fernandez, *et al*., 2025). Due to the limited efficiency of conventional treatment systems, these compounds are not completely eliminated and are consequently discharged into different environmental matrices in concentrations ranging from ng to µg L^{-1} (Trawiński and Skibiński, 2023). While some sweeteners such as aspartame degrade relatively quickly (Ma *et al*., 2021) others, such as sucralose and acesulfame-K, resist purification processes and remain in aquatic ecosystems resulting in a high persistence (Tollefsen, Nizzetto, and Huggett, 2012).

1.3.10 Disinfection by-products (DBPs)

Disinfection byproducts (DBPs) are a family of well-known secondary pollutants formed by the reactions of chemical disinfectants with DBP precursors during water disinfection treatment. They are formed by the unintended reactions of chemical disinfectants with certain water matrix constituents, known as DBP precursors like natural organic matter (NOM), anthropogenic contaminants, and halides (Richardson, Plewa, Wagner, Schoeny, and Demarini, 2007; Xiao, *et al*., 2023; Xiao, Deng, Xu, and Chu, 2024). DBPs have gained a great deal of attention due to their potential adverse health effects (Li, and Mitch, 2018). Considerable interest has been directed to the impacts of natural processes and human activities on DBPs and DBP precursors in drinking water sources. Inappropriate disposal and leakage of bromide- and iodide-containing wastewater from hydraulic fracturing can lead to an increase in these unwanted halides in raw water and further promote the production of DBPs, especially highly toxic brominated and iodinated DBPs (Parker, Zeng, Harkness, Vengosh and Mitch, 2014; Xiao *et al.*, 2024).

Disinfection chemicals used in swimming pool and drinking water purification are key components shielding humans from water-borne diseases. (Villanueva, Cordier, Font-Ribera, Salas and Levallois 2015). More than six hundred DBPs have been discovered, including iodinated trihalomethanes (THMs). They are usually oxidizing agents, possess strong chemical activities that not only eliminate pathogenic agents but also react with many deoxidizers (Hua and Reckhow, 2007). The widespread and frequent use of these chemicals produces disinfection byproducts (DBPs), particularly chlorinated DBPs (CDBPs) in purified water, and nearly all humans are exposed to these chemicals in developed regions through swimming pools and drinking water (Fantuzzi, Aggazzotti and Righi, 2007; Richardson and Ternes, 2014).

1.3.11 Perfluorochemicals

Perfluorochemicals (PFCs) are a family of synthetic, anthropogenic hydrophobic and lipophobic chemicals of unusual compounds that do not occur naturally. The chemical structures of PFCs make them very resistant to degradation in the environment (Arguello-Pérez *et al.,* 2019). This diverse group of compounds is characterized by multiple fluorinated carbon-fluorine bonds that confer unique properties such as heat, water, and oil resistance. The two most common groups of PFCs that are measured and detected in environmental matrices are perfluoroalkyl sulphonates (PFASs) with main representative compound perfluorooctane sulphonate (PFOS) and perfluoroalkyl carboxylates (PFACs), with main representative compound perfluorooctanoic acid (PFOA). The exceptional chemical and thermal stability has led to their extensive utili zation in a wide range of industrial and consumer applications, including firefighting foams and water-repellent coatings among other various manufacturing processes (Evich *et al.,* 2022). Specifically, long-chain PFAS like perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) have been phased out globally because of their toxicity and environmental persistence (Zheng *et al.,* 2023; Li *et al.,* 2024).

1.3.12 Cyanotoxins and other algae toxins

Cyanobacterial Harmful Algal Blooms (CyanoHABs) occur in diverse surface waters. These toxins can contaminate drinking water sources and have been linked to a range of health issues (Harke, Steffen, Gobler, Otten and Wilhelm, 2016). Cyanobacterial blooms stimulated by multiple factors have led to a significant increase in the frequency, distribution range, intensity, and duration of cyanobacterial blooms, thus further exacerbating the risk of algal toxin poisoning (Zhang, Duy and Munoz, 2022; Huisman, Codd and Paerl, 2018). There can occur in most freshwater including wetland, lakes, reservoirs, streams and rivers.These blooms are characterized by the rapid proliferation of Cyanobacteria that produce toxic metabolites known as cyanotoxins. The release of these toxin into the surrounding water are mostly during cell rupture. However, some species are capable of releasing toxins into the water without cell rupture or death causing numerous health effect such as diarrhea, headache or skin irritation. Under the right condition cynobacterials blooms can produce toxic byproduct known as cyanotoxin.

Cyanotoxins can be classified into three groups based on their chemical structure: cyclic peptide, alkaloid and lipopolysaccharide (LPS). Depending on the mode of toxicity to animals, toxins can be classified as hepatotoxic cyclic peptide toxins (represented as microcystin and nodularin), neurotoxic alkaloidal toxins, cytotoxic alkaloidal toxins, dermatologic toxicity of alkaloidal toxins, irritant toxins (LPS), and some other biologically active substances. The occurrence of cyanotoxins in different water systems has been extensively studied in high-income countries (Loftin *et al.,* 2016; Bormans *et al.,* 2019; Zhang *et al.,* 2021; Fastner *et al.,* 2023) and, to a lesser extent, in developing countries (Huo *et al*., 2022; Wang, Zhang, Mu, Hu and Ma 2023; Falfushynska, Kasianchuk, Siemens, Henao and Rzymski, 2023). Recent reviews have explored various aspects of cyanotoxins, including (1) their presence in aquatic ecosystems and organisms such as fish, with a limited focus on drinking water systems (Falfushynska *et al.,* 2023)

Globally, microcystin-LR is the most common cyanotoxin in freshwater, brackish water, and marine habitats (Massey, Al Osman and Yang, 2022). Lakes and reservoirs differ in morphology and trophic status, which can affect the dispersal and distribution of cyanotoxins (Wood, Maier and Puddick, 2017). Cyanotoxins are also subject to transport and diffusion at the sediment-water interface, with different types of sediments exhibiting different adsorption capacities (Liu, Mazmouz and Pearson, 2019). Moreover, cyanotoxins in the atmosphere may, under certain conditions, settle on the ground or in water bodies and affect the surrounding environments (Wiśniewska, Śliwińska-Wilczewska and Savoie, 2022).

1.3.13 Radionuclides and nuclear wastes

Radionuclides are unstable atomic nuclei that release energy in the form of radiation as they decay into more stable forms (Gwynn, Hatje, Casacuberta, Sarin and. Osvath, 2024). Radionuclides can be categorized into two broad types: natural and anthropogenic. Natural radionuclides are those that occur naturally in the environment, such as uranium, thorium, and radon, whereas anthropogenic radionuclides are the result of human activities, including nuclear accidents, industrial processes, and military actions (Wong, *et al.*, 2025). The sources of environmental radionuclide contamination are diverse, involving both natural and human-driven processes. Radionuclides are found everywhere in the environment. In principle, every individual on earth is naturally exposed to ionizing radioation. They pose considerable challenges to environmental quality and human well-being whether released from nuclear power plants, medical facilities, or sites where radioactive material was improperly disposed of (Santhanabharathi, Pradhoshini and Suhail, 2023). Nuclear accidents, such as the catastrophic releases at Chernobyl and Fukushima, have led to the widespread contamination of land, water, and air with radionuclides (Ambrosino, Gargiulo, Peruta, Gravino and Gagliardo, 2023; Seyama, Arakawa, Machida, Yoshida and Maru, 2020). Mining and industrial activities, particularly uranium mining and nuclear fuel reprocessing, contribute significantly to environmental contamination. Natural sources, such as the radon gas released from uranium decay and cosmic radiation from outer space, also add to the environmental burden of radionuclides (Bem, Długosz-Lisiecka, Mazurek-Rudnicka and Szajerski, 2021; Rodriguez, Majumdar, Meza, Corcoran, and Pierson, 2024)**.** Exposure to radionuclides poses significant health and environmental risks. Ionizing radiation emitted by radionuclides can damage cellular DNA, leading to mutations, carcinogenesis, and other health issues such as immune system suppression.

1.3.14 Microplastics and nanoplastics

Microplastics (MPs) are defined as plastic particles less than 5 mm in size, originating from the breakdown of larger plastic debris or microbeads. Microplastics, minuscule plastic particles often found in the environment, are a biological contaminant with far-reaching consequences and can be ingested by aquatic organisms and accumulate in food chains, posing risks to both aquatic life and humans (Li and Liu, 2016). When ingested by aquatic organisms, microplastics cause both physical and chemical harm. Recent research has demonstrated that microplastics are a severe environmental pollutant due to their accumulation, threatening ecosystems and organisms worldwide. These particles have been detected in various habitats, including freshwater, marine, soil, and air. Studies have shown microplastics can inhibit seed germination, root growth, and nutrient uptake in plants, negatively impacting terrestrial environments (Rede *et al.*, 2023). Moreover, emerging threats like microplastics further degrade habitats, impacting the physical environment and the organisms reliant on these spaces. Microplastics pose ingestion risks to wildlife and disrupt habitats, with recent research suggesting that they might alter soil nutrient dynamics by reducing leaching. Such findings highlight the complex interactions between pollutants and ecosystem processes, underscoring the urgent need to mitigate these environmental pressures (Haque and Fan, 2023; Morin-Crini, Lichtfouse and Liu, 2022). Additionally, microplastics represent a significant global problem for terrestrial and aquatic ecosystems, as toxicological testing has found they can enter various organisms' digestive systems. This can lead to gut blockage, physical damage, histological changes, and oxidative stress (Song *et al.*, 2023).

1.3.15 Nanomaterials

Nanotechnology is one of the most exciting and fast-moving areas of science today. It has been advantageous in many sectors, like medicine, the military, electronics, food, chemicals, energy and a wide variety of other scientific fields (Wongrerkdee, Wongrerkdee, Boonruang and Sujinnapram, 2023; Yi, *et al.,* 2023; Ezzeddine, Batonneau-Gener, Pouilloux, 2023). However, nanomaterials (NMs) are considered emerging environmental contaminants due to their unique physiochemical properties such as high surface area, tunable surface chemistry and catalytic activity.Nanomaterials exhibit unique physical, chemical, and biological properties due to their nanoscale dimensions, typically ranging from 1 to 100 nm in size. They have a high surface-to-volume ratio, influencing their behavior. These materials have exceptional properties, enabling applications in electronics, energy, biomedicine, and more. Nanomaterials' versatility and properties have made them increasingly important in various industries, driving advancements in electronics and energy to healthcare and environmental technology (Pomerantseva *et al.,* 2019). However, nanomaterials' small size and high surface-to-volume ratio have also raised concerns about their potential impact on human health and the environment. Hao *et al.* (2019) stipulated that mesoporous carbon nanoparticles can cause phytotoxicity in rice seedlings, and their size effects contributed greatly to causing phytotoxicity in plants (Hao *et al.,* 2019). Nanoplastics (NPs) more negatively affected plant development parameters, photosynthetic pigments, and biochemical indicators than microplastics (Li *et al.,* 2024).

2.0 Sources and pathways of Emerging Pollutants

Water pollution is a global problem that needs urgent attention and the implementation of a better plan to find a solution. To better understand and address ECs and their harmful impacts, it is crucial to thoroughly analyze the characteristics of these substances, how they are released into the environment, and how they can affect living organisms. The sources of these contaminants are varied spanning agricultural runoff, industrial emissions and domestic waste. They can enter the environment through multiple pathways, such as leaching, atmospheric deposition, and discharge in wastewater (Khan *et al.,* 2022; Satyanarayana *et al.,* 2023). Common introduction routes include wastewater effluent from manufacturing facilities, land application of biosolids, landfill leaching, urban and agricultural runoff, and atmospheric deposition. Grasping these introduction pathways is essential for formulating approaches to moderate their influence. A comprehensive understanding of contaminant transport routes into the environment facilitates the development of evidence-based solutions to address this pressing issue (Li, Shen, Jiang, Xi and Li, 2024). Emerging pollutants may enter the groundwater directly by discharge of contaminants into the ground or may enter through polluted surface water (Bayabil, Teshome and Li, 2022; Khan *et al*., 2021). The aquatic environment is under severe threat caused by a number of emerging contaminants originating from the disposal and diffusion of pollutants.

2.1 Industrial Discharges

Industrial and manufacturing processes frequently result in the discharge of ECs into local water systems. These discharges are a significant source of emerging contaminants, often including a variety of chemical pollutants (Johnson and Martinez, 2017). Industrial processes frequently result in the discharge of a variety of chemicals utilized in production, processing, and mining operations released through wastewater effluents and subsequently introduced risks to environmental resources. A variety of chemicals utilized in production, processing, and mining operations can be released through wastewater effluents and subsequently introduce risks to environmental resources. Recent research has brought attention to the threats posed by contaminants entering sewer networks and transferring microplastic debris resulting from the extensive use of plastic mulching film into receiving bodies of water (Jan, Mishra, Bhat, Bhat and Jan, 2023; Kumar, Xiong and He, 2020) and pathogens introduced through the application of livestock manure or WWTP biosolids as fertilizer (Buta, Hubeny and Zieliński, 2021) These discharges can lead to contamination of nearby water bodies and soil. Recent research has brought attention to the threats posed by contaminants entering sewer networks and transferring into receiving bodies of water (Jan *et al*., 2023). Studies have also assessed sediment concentrations of polycyclic aromatic hydrocarbons, benzene, toluene, ethylbenzene, and xylenes, as well as emerging pol lutants, in specific geographies like the Chanomi Creek region of the Niger Delta (Li *et al.,* 2024). As anthropogenic ac tivities introduce new substances into the aquatic environment, continued evaluation remains essential for safeguarding water and habitat quality (Onyena *et al.,* 2023).

2.2 Urban Runoff

Urban runoff, especially from densely populated areas, can contain a range of contaminants from various sources, including roads and residential zones (Green and White, 2018). It is a complex pathway for the introduction of contaminants into water bodies.

2.1.3 Agricultural Runoff

Agricultural runoff contributes to the introduction of contaminants into the environment, primarily through the leaching of pesticides and fertilizers (Smith and Brown, 2015). This runoff can contaminate surface waters and groundwater. Agricultural practices can inadvertently introduce ECs into the environment if not properly managed. Fertilizers, pesticides, and veterinary drugs applied to agricultural fields may gradually leach into surrounding soil and water sources over time. Additionally, there is a risk for these pollutants to enter the atmosphere through agricultural spray drift or volatilization following pesticide application (Wilkinson, Hooda and Barker, 2017). Fertilizers, pesticides and veterinary drugs applied to agricultural fields may gradually leach into surrounding soil and water sources over time. Recent academic studies have highlighted how certain agricultural activities can disperse con taminants (Santos *et al.,* 2022). Without significant alterations to existing practices, new pollutants produced by farming are expected to continue accumulating in soils, potentially polluting nearby water bodies through surface runoff and infiltration (Morin-Crini, Lichtfouse and Liu, 2022). Recent academic studies have highlighted how certain agricultural activities can disperse contaminants (Santos et al., 2022). For instance, fertilizer use may spread pharmaceuticals and personal care products, wastewater treatment facilities may insufficiently remove ECs, aquaculture can accumulate heavy metals in sediments from fertilizer runoff, and nanotechnology in farm chemicals poses implications for pollution minimization. Improved practices are needed to apply, treat, and contain agricultural outputs to restrict the accidental dispersion of contaminants from unintended agricultural sources and their effects on the environment. Overall, stewardship is essential to sustainably safeguard soil and water quality (Hossain *et al*., 2023).

2.4 Atmospheric Deposition

This pathway may include airborne pollutants, particulate matter from industrial emissions and vehicular exhaust from industrial and urban sources (Barroso *et al.,* 2019). Tu *et al.* (2024) examined the spatiotemporal variation and inter-transport of atmo spheric pollutants, including mercury, between urban areas and a har bor, emphasizing the role of vehicular exhausts and industrial emissions in atmospheric transport (Tu *et al*., 2024). Specific ECs can be transported through the atmosphere and deposited in distant locations. Atmospheric deposition, such as the settling of pollutants from the air, can lead to the introduction of contaminants into terrestrial and aquatic environments (Jones et al., 2015).

2.5 Groundwater Contamination

Groundwater contamination can occur due to the infiltration of contaminants from the surface, such as agricultural runoff and industrial discharges (Hassan *et al*., 2019). It poses a risk to drinking water sources.

2.6 Food Chain Contamination

Food Chain Contamination refers to the process where toxic substances enter the environmental matrices through ecosystems and accumulate in edible agricultural or aquatic products. Food production has significantly increased in recent years to meet the growing global demand. As a result, agricultural activities have become common contributors to releasing emerging pollutants into the environment (Evans, Mateo-Sagasta and Qadir, 2019; Nguyen, Lin and Nguyen, 2023). This is often linked to the discharge of agrochemicals, antibiotic residue from livestock wastes (Nguyen, Lin and Nguyen, 2023). Contamination of the food chain can occur when contaminants from the environment are absorbed by plants or consumed by animals, eventually affecting human food sources (Luo and Martinez, 2024). This pathway can have significant implications for human health

2.7 Improper disposal and leaching

Improper disposal of products with ECs, such as electronics and plastics, results in environmental contamination. These products release micro- and nano-plastics and hazardous substances into soil and water, leading to widespread pollution, evidenced by their presence in water sources, treatment plants, and drinking water. Heavy metals and other toxins are discharged as electronic wastes which adversely affecting both terrestrial and aquatic ecosystems (Pathak and Sushil, 2022). Beyond the discharge of effluents from WWTPs and agricultural activities, leachate from landfills, where household wastes are deposited, constitutes a significant source of emerging pollutants in terrestrial ecosystems (Eggen, Moeder and Arukwe, 2010; Qi, Huang and Wang, 2018; Qian, Hu and Lang-Yona, 2023; Rogers, Zalensky and Lin, 2021). PPCPs, endocrine-disrupting chemicals, and ARGs have been detected in untreated landfill leachate at concentrations ranging from ng/L to µg/L (Qi, Huang and Wang, 2018), with some concentrations surpassing proposed safe thresholds for the emergence of antibiotic resistance (Bengtsson-Palme and Larsson, 2016; Chung, Zheng and Burket, 2018). When these potentially toxic leachates seep out or overflow into water bodies, they can adversely affect aquatic organisms (Rogers, Zalesny and Lin, 2021). The exposure to these contaminants poses significant health risks, with electronic waste leachate containing harmful toxins. Furthermore, the accumulation of micro- and nano-plastics disrupts ecosystem balance, threatening biodiversity by harming soil organisms and plant and ani mal life (Pradhan *et al.*, 2023; Rathi *et al.*, 2021).

2.8 Sewage systems

Wastewater treatment is crucial for handling ECs like drugs and personal care waste, which often enter water bodies due to incomplete removal by treatment plants. Studies show the importance of enhancing removal methods in constructed wetlands and these pollutants' health and environmental risks. The literature points out the challenges and impacts of inadequate sewage treatment on managing such residues, stressing the need for better treatment processes (Singh *et al.*, 2021).

3.0 Environmental and Human Health Impacts

Emerging pollutants (EPs) pose a growing environmental and public health concern due to their persistence, bioactivity, and resistance to natural degradation processes, which enables them to accumulate in ecosystems and pose significant long term threats to both environmental and human health. This section explores the multifaceted impacts of EPs, highlighting their ecological consequences, human health risks, and economic implications. Emerging pollutants pose a unique and escalating challenge due to their potential to disrupt ecosystems and public health. Despite their often low concentrations, their biological activity and cumulative effects can lead to significant ecological and health risks (Annamalai and Namasivayam, 2015; Pan, Liu, Yu, Zhang and Liu, 2024). These contaminants often evade conventional treatment processes and accumulate in water, soil, and biota. Their continued release into the environment disrupts natural ecological functions, threatens biodiversity, and contributes to long-term health risks. The bioactivity of EPs, even at trace concentrations, presents another challenge. While these contaminants may be present at levels as low as nanograms per liter (ng/L) in surface waters, their continuous input from wastewater, industrial discharges, and agricultural runoff contributes to chronic exposure for organisms and humans (Paiu, Favier and Gavrilescu, 2024).

3.1 Socio-economic implications

The persistence of emerging pollutants (EPs) in the environment has far-reaching socio-economic consequences, affecting public health systems, industries, and environmental management policies. From an economic and regulatory standpoint, the presence of EPs in the environment poses significant challenges. The economic burden associated with EP contamination extends beyond direct remediation costs, encompassing healthcare expenses, reduced agricultural and fisheries productivity, and the long-term degradation of natural resources (Paiu, Favier and Gavrilescu, 2024). One of the most significant financial impacts of EPs is the cost of upgrading water treatment infrastructure to remove contaminants that evade conventional wastewater treatment processes. The costs associated with mitigating their impacts, including upgrading wastewater treatment facilities, remediating contaminated ecosystems, and addressing healthcare burdens related to pollutant exposure, place considerable strain on governments, industries, and communities (Paiu *et al.*, 2024). Advanced treatment technologies, such as membrane filtration, advanced oxidation processes, and activated carbon adsorption, require substantial investments in equipment, operational maintenance, and energy consumption. Many municipalities, particularly in low-income regions, lack the financial and technical capacity to implement such upgrades, leading to prolonged exposure to contaminated water supplies (Zhang, 2025; Kathi and El Din Mahmoud, 2024).

The healthcare sector also bears a significant economic burden due to the long-term health effects associated with EP exposure. Antibiotic resistance alone is estimated to cost healthcare systems billions of dollars annually due to extended hospital stays. In addition to public health concerns, EPs negatively impact key economic sectors such as agriculture, fisheries, and tourism. Contaminated irrigation water can introduce toxic substances into crops, reducing agricultural yields and posing risks to food safety. Similarly, pollutants accumulating in fish and seafood not only threaten aquatic biodiversity but also reduce the marketability of fishery products, leading to economic losses for fishing communities. In areas dependent on ecotourism, environmental degradation caused by EP contamination can result in decreased revenue and job losses (Ulucan-Altuntas *et al.*, 2023; Wang, Xiang and Sze-Yin, 2024). Moreover, the remediation of ecosystems affected by EPs requires long-term financial and logistical commitments. Cleaning up polluted water bodies, rehabilitating contaminated soils, and restoring biodiversity demand extensive research, monitoring, and technological interventions.

3.2. Effects on ecosystems

Emerging pollutants (EPs) pose a significant threat to ecosystems by altering the physiological and behavioral responses of organisms, leading to disruptions in natural ecological processes. Agricultural runoff, enriched with nutrients and pollutants, disrupts ecosystem nutrient cycles, leading to eutrophication. Pharmaceuticals, such as antidepressants and anxiolytics, have been shown to alter fish behavior, reducing predator avoidance and affecting feeding patterns (Li *et al.*,2024). Similarly, endocrine-disrupting chemicals (EDCs), including certain pesticides, plasticizers, and industrial byproducts, interfere with hormonal regulation in wildlife, leading to reproductive abnormalities, reduced fertility, and developmental defects in offspring. Amphibians, fish, and invertebrates are particularly vulnerable to these disruptions, which can have cascading effects throughout food webs (Gomes, Maillard, Simões and Simões, 2020; Jan *et al.*, 2023; Li *et* *al.*,2024). The destabilization of ecosystems caused by EP exposure can lead to biodiversity loss and shifts in species composition. For instance, the presence of antibiotics in aquatic environments can alter microbial communities by selectively eliminating sensitive species while promoting the proliferation of antibiotic-resistant bacteria. These changes disrupt ecological balance and nutrient cycling, with potential consequences for water quality and ecosystem resilience (Ulucan-Altuntas *et al.,* 2023). These contaminants enter the environment through wastewater discharge, agricultural runoff, and industrial emissions, accumulating in aquatic and terrestrial habitats (Melchor-Martínez *et al.,* 2021; Chaturvedi *et al*., 2021).

Furthermore, many EPs exhibit persistence in the environment, allowing them to bioaccumulate in organisms and biomagnify as they move up the food chain. This is especially problematic for top predators, such as birds of prey, marine mammals, and large fish species, which experience higher contaminant loads due to their dietary habits. The accumulation of persistent pollutants, such as pharmaceuticals, flame retardants and per- and polyfluoroalkyl substances (PFAS), has been linked to immune suppression, neurological impairments, and increased susceptibility to disease in wildlife (Mishra, Mentha, Misra and Dwivedi, 2023; Morales *et al.,* 2024; Sharma *et al.,* 2014). Given these ecological risks, addressing the persistence and impact of EPs requires integrated monitoring programs, stricter regulations, and the development of environmentally friendly alternatives to minimize their release into natural ecosystems.

3.3 Impacts on wildlife

Many EPs act as endocrine disruptors, neurotoxins, or carcinogens, with the potential to alter reproductive cycles, impact metabolic processes, and induce long-term health effects. ECs, particularly endocrine-disrupting chemicals (EDCs), pose significant risks to wildlife by disrupting animal hormonal systems. After slipping through sewage treatment plants, these con taminants have been detected in various environmental matrices, including streams, lakes, and groundwaters worldwide. Not only can pharmaceutical exposure alter reproductive behaviors in aquatic species like fish and amphibians but also industrial by-products have shown direct toxicity, increasing mortality and jeopardizing population sustainability. Additionally, environmental contaminants like diclofenac, Ivermectin, has been shown to have a significant toll on wild animals, with effects that can be acute, chronic, secondary, or indirect (LAM *et al.,* 2019; Sonne *et al.*, 2021). The detrimental effects of EDC pollution on marine organisms' health, reproduction, and development have been underscored by recent research, highlighting the environmental threat of pharmaceuticals and personal care products. Enhancing methods for elimi nating these ECs is necessary to safeguard wildlife and maintain ecosystem health and resilience (Khan *et al.,* 2022).

3.4. Biodiversity loss

Introducing toxic pollutants into ecosystems can be significantly reduced and be felt in a far distance. Specific ECs can be transported through the atmosphere and deposited in distant locations. This includes particulate matter from industrial emissions and vehicul**ar exhaust**. Prolonged exposure to ECs may cause genetic alterations, diminishing genetic diversity and weakening population resilience (Reid et al., 2019). These pollutants can modify gene expression in aquatic species directly through water contamination and indirectly via the food chain, leading to widespread ecological and molecular disruptions. **Recent s**tudies have shed light on this phenomenon (Barroso et al., 2019). For instance, Tu *et al*. (2024) examined the spatiotemporal variation and inter-transport of atmo spheric pollutants, including mercury, between urban areas and a harbor, emphasizing the role of vehicular exhausts and industrial emissions in atmospheric transport (Tu *et al.*, 2024).

3.5 Human health impacts

Environmental pollution is escalating due to rapid global development that often prioritizes human needs over planetary health. Despite global efforts to mitigate legacy pollutants, the continuous introduction of new substances remains a major threat to both people and the planet. The presence of emerging pollutants (EPs) in the environment poses a growing threat to human health, as these contaminants often persist in water, soil, and food sources, leading to continuous low-dose exposure. They exhibit biological activity even at trace concentrations, potentially causing long term adverse health effects (Annamalai and Namasivayam, 2015; Sharma *et al.,* 2014). ECs such as pharmaceuticals, personal care products, and micro plastics pose increasing risks to human health. Effects on human health may include hormonal disruptions, antibiotic resistance, and other long-term impacts, prompting a need for public health systems to evolve and address these challenges (Yadav *et al*., 2021). Furthermore, the contamination of drinking water with EPs and heavy metals, presents a direct threat to public health,. Chronic exposure to these contaminants has been linked to a range of health disorders. Vulnerable populations, such as pregnant women, infants, and individuals with pre-existing health conditions, are particularly at risk from long-term EP exposure (Kim and Kang, 2021; Li, Shen, Jiang, Xi and Li, 2024; Wang, Xiang and Sze-Yin, 2024). Humans and other living things are at greater risk from eating plants and seafood that have been polluted by contaminated soil or water. Crop contamination occurs when toxins are absorbed by the roots of the plants from the soil and water. On the other hand, aquatic organisms were bio-accumulated with contaminants from polluted water and through their food (Alengebawy, Abdelkhalek, Qureshi and Wang, 2021; Saher and Kanwal, 2019). The effects on humasn are listed as follows:

3.5.1 Antibiotic resistance and infectious diseases

PPCPs (antibacterial creams and ointments), when improperly used, disposed of, or inadequately treated, could contribute to the development of ARBs. One of the pressing and increasing health threats posed by ECs is the rise of antibiotic resistance. The widespread use has led to their continuous release into the environment, creating reservoirs of antibiotic-resistant bacteria in wastewater, agricultural runoff, and drinking water sources. This has severe implications for global healthcare (Baralla, Demontis, Dessì and Varoni, 2021; Cedeño-Muñoz, Abiodun and Venkateswar, 2024). This outcome poses a significant threat to public health as conventional treatments become less effective, leading to an increased prevalence of infectious diseases. For example, symptoms of infectious diseases, particularly those related to airway infections were much more common among individuals with compromised health or chronic conditions who used antibacterial medications.

3.5.2 Endocrine disruption and reproductive disorders

Endocrine disruption EDCs, including bisphenol A (BPA) and phthalates represent a class of ECs that mimic or interfere with the endocrine hormones, often acting as agonists or antagonists and to interfere with the body’s hormonal systems, potentially leading to adverse health effects. Studies have linked prenatal and early life exposure to EDCs with neurodevelopmental impairments, obesity, and immune dysfunction, raising concerns about transgenerational health effects (Ahn and Jeung, 2023; Ayaliew. Gebru, Redae and Tsige, 2022; Dong *et al.*, 2022). Endocrine-disrupting chemicals primarily target the female reproductive system. They can increase the risk of various reproductive disorders, including fertility issues, developmental abnormalities, and hormone-sensitive cancers.

In humans, prolonged exposure to persistent pollutants such as per-and polyfluoroalkyl substances (PFAS), bisphenol A (BPA), and certain pharmaceuticals has been associated with cancer, endocrine dysfunction, and developmental disorders (Arman *et al.*, 2021; Yadav *et al.,* 2021). Specifically, BPA and phthalates have been linked to obesity, altered reproductive behaviors, and decreased fertility in humans and wildlife (Dong *et al.*, 2022). The mechanisms through which these chemicals act include binding to hormone receptors, altering hormone synthesis, and affecting signal transduction pathways (Li *et al.,* 2024). Developing safer alternatives and stricter regulatory measures is crucial to mitigate their widespread effects (Pan *et al.,* 2024).

3.5.3 Carcinogenic effects

It has been established that PFAS are linked to cancer, including breast cancer, due to their endocrine-disrupting effects and interference with hormones (Evich *et al.,* 2022). Long-term, low-level exposure to PFAS increases cancer risk, particularly breast cancer, by mimicking estrogen and promoting tumor growth in breast tissue. This connection, proven by epidemiological research, highlights the critical need for more research on PFAS's carcinogenic mechanisms and ways to reduce exposure (Seyyedsalehi and Boffetta, 2023). The prevalence of Micro plastics and Nanomaterials in various consumer products and industrial processes has also raised concerns about their potential to contribute to the development of cancer, as these minute particles may interact with biological systems in complex and unpredictable ways (Winiarska *et al.*, 2024).

3.5.4 Cardiovascular and metabolic effects

The ECs are of particular concerning, as they have been linked to the development and progression of various cardiovascular diseases through different mechanisms. Their harmful effects on the cardiovascular system are diverse, ranging from direct interference with cellular signaling pathways to the induction of oxidative stress and inflammation. The metabolic consequences of these contaminants are alarming due to the fact that they disrupt the endocrine function, impair glucose homeostasis and contribute to the development of metabolic disorders. Also recent studies link PFAS exposure to car diovascular and metabolic issues through oxidative stress and changes in lipid metabolism (Dunder et al., 2023). This increases the risk of heart disease, stroke, and type 2 diabetes. PFAS may also cause sys temic inflammation and metabolic problems, raising cardiovascular disease risks. (Meneguzzi *et al.,* 2021).

3.5.5 Respiratory effects *(cardiopulmonary diseases)*

Industrial pollutants, especially fine particles, are a major threat to lung health, causing asthma and COPD. The EPA warns that these par ticles can cause severe asthma attacks and hospital visits. Airborne particulates can carry various ECs, including heavy metals (metalloids), POPs, NPs, and even viruses. The respiratory systems become the primary targets, with potential consequences ranging from irritations (e.g., coughing) to chronic cardiopulmonary diseases (hypertension and chronic obstructive pulmonary diseases). Studies show that long-term exposure to these pollutants increases asthma risk in kids and worsens COPD in adults, with year-round exposure heightening asthma rates in children and exacerbating COPD symptoms in adults (Josa-Culler´ e *et al*., 2024).

3.5.6 Neurotoxicity

Chronic exposure, even at sublethal levels, has been associated with exacerbated neurotoxic effect. Substantial evidence suggests that certain ECs, such as heavy metal, cyanotoxins and POPs possess neurotoxic properties. Recent research highlights the neurotoxic effects of certain pesticides and industrial chemicals, underscoring their potential to induce neuro logical damage in humans. Increased risk of neurological disorders, including cognitive impairments, developmental delays, and neurodegenerative diseases are associated with chronic exposure to these substances These substances have been increasingly recognized for their capacity to interfere with neurochemical reactions, leading to neurodevelopmental abnormalities and heightening the risk of neurodegenerative diseases such as Alzheimer's and Parkinson's (Kumar *et al*., 2023; Li *et al*., 2024). Studies have documented the mechanisms through which these chemicals induce neurotoxicity, including the disruption of neurotransmitter systems, oxidative stress, and direct neuronal damage.

This body of evidence calls for stringent regulatory measures and further investigation to under stand the full extent of their impact on human health and to develop effective strategies for mitigation and prevention (Finhler *et al.*, 2023).

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3.5.7 Immune system impacts and allergic reactions

ECs may influence the immune system, potentially leading to compromised immunity or triggering allergic reactions. Studies have reported that these substances can affect the activation and survival of immune cells, potentially contributing to allergic rhinitis and other allergic responses. Recent studies show environmental pollutants like heavy metals and industrial by-products harm the immune system, potentially causing autoimmune diseases. These substances can weaken immune responses and increase susceptibility to diseases and severe allergic reactions (Li *et al.*, 2024). Pollutants can change immune tolerance, affect immune cells, and disrupt gut health, which is crucial for immune balance (Suzuki *et al.*, 2020). According to Lou *et al*., (2024) trichloroethylene affects gut barrier function, and cadmium can lead to inflammatory conditions. Pollutants also alter epigenetic mechanisms related to autoimmune diseases. This evidence calls for more research and stricter regulations to reduce exposure and protect health (Lou *et al*., 2024).

3.6 Human Exposure Routes

A. Ingestion

Ingestion is a common route of exposure to emerging contaminants. Research indicates that the ingestion of contaminated water or food can lead to the intake of various contaminants, including pharmaceuticals and pesticides (Smith and Brown, 2015).

B. Inhalation

Inhalation is another exposure route, particularly for contaminants present in the air. Studies have shown that airborne contaminants, such as particulate matter and volatile organic compounds, can be inhaled, potentially impacting respiratory health (Li and White, 2016).

C. Dermal Contact

Dermal contact refers to exposure through the skin. Personal care products containing contaminants, as well as contaminated water in recreational settings, can result in dermal exposure to emerging contaminants (Green and Davis, 2017).

Conclusions

Emerging contaminants and emerging issues about soil, air and water contamination have been around without our knowledge for millennia and we can hope that as environmental chemistry, health and environmental toxicology improves, we can do a better job to prevent deleterious effects upon our environment and our health and reduce the number of situations where we wait until the damage is rampant before we enforce some form of regulation.

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