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REVIEW ARTICLE

Pollutants in aquatic system: a frontier perspective of emerging threat and strategies to solve the crisis for safe drinking water

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Abstract

Water is an indispensable natural resource and is the most vital substance for the existence of life on earth. However, due to anthropogenic activities, it is being polluted at an alarming rate which has led to serious concern about water shortage across the world. Moreover, toxic contaminants released into water bodies from various industrial and domestic activities negatively affect aquatic and terrestrial organisms and cause serious diseases such as cancer, renal problems, gastroenteritis, diarrhea, and nausea in humans. Therefore, water treatments that can eliminate toxins are very crucial. Unfortunately, pollution treatment remains a difficulty when four broad considerations are taken into account: effectiveness, reusability, environmental friendliness, and affordability. In this situation, protecting water from contamination or creating affordable remedial techniques has become a serious issue. Although traditional wastewater treatment technologies have existed since antiquity, they are both expensive and inefficient. Nowadays, advanced sustainable technical approaches are being created to replace traditional wastewater treatment processes. The present study reviews the sources, toxicity, and possible remediation techniques of the water contaminants.

Keywords Environment · Industries · Pollution · Remediation · Toxicity · Nanoparticles

Introduction

Water-an unprotected natural resource, is crucial for both human and economic prosperity (Ilori et al. 2019; Opafola et al. 2020). It occupies 71% of the earth's surface. Of this, a major proportion (~95.6%) confined to seas cannot be used for human purposes without going through a tedious desalination process (Ajibade et al. 2021). As the world's population continues to expand at an alarming rate, fulfillment of the requirements of the growing population has led to the exploitation of resources and pollution of the environment (Okello et al. 2015). Hazardous wastes from power plants, metallurgy, distilleries, textile, paper, dye, and drug industries enter water bodies directly, thereby making the water unfit for human purposes (Haseena et al. 2017). The pollutants include compounds of both inorganic (heavy metals, etc.) and organic (detergents, pesticides, and others) nature including personal care products (PCPs), pharmaceuticals, pesticides, flame retardants, detergents, surfactants, and others, discharged directly into the environment for which no restrictions are imposed (Daughton 2003). Originating from the release of treated and untreated effluents from different setups into aquatic resources, the pollutants produce a detrimental impact on the aquatic and terrestrial organisms, besides affecting plant systems right from seed germination to enhancement in the production of reactive oxygen species (ROS) that affect cellular components with significant impact on the overall development of plant and their yield (Haseena et al. 2017). Together, pollution of water resources often led to its shortage with considerable effect on human survival, industrial development, and the environment.

Safeguarding the right of citizens to clean and safe drinking water, and abatement of pollutants from the water bodies, is categorized as the top priority in different countries

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(Mekonen et al. 2016). Adaptation of a proper treatment strategy for the removal of pollutants in water bodies varies according to its nature, friendliness, affordability, effectiveness, and reusability (de Souza et al. 2020a, b). As traditional treatment strategies are expensive and inefficient in achieving the goal of clean water, the development of an effective and sustainable remedial strategy seems the only possible alternative. Herein, the study was undertaken to review important aspects of the pollutants in the aquatic ecosystem, may it be the source, toxicities associated with different pollutants, and the possible remedial strategies so as to minimize their impact on the environment and on human health.

Pollutants, pollution, and the environment

The planet Earth is presently facing serious environmental challenges including global warming, contamination of water resources along with others such as depletion of energy sources (Ahmad et al. 2013; Wang et al. 2018). Of them, pollution of the water bodies with a diverse blend of substances of both organic and inorganic nature generated from different point sources preferably from industries, agricultural practices, and pharmaceutical companies, besides having a definite proportion of household release, makes it unfit for human use. The release of pollutants ranging from organic (polycyclic aromatic hydrocarbons (PAHs), fats, sugars, and amino acids released as untreated sewage), inorganic (heavy metals, ammonium salts, etc.) to synthetic (polychlorinated biphenyls (PCBs), pesticides, etc.) imposes a huge impact on the environment with a toxic effect on different life forms (Hasan 2014; Deka and Lahkar 2017; Ding and Lisak 2019; Ahamad et al. 2021). Representing a problem of increasing concern that poses increasing hazards to human health and the well-being of global flora and fauna, if left unaddressed, would result in different societal and technological challenges with serious consequences at both regional as well as at the global scale.

The emergence and continual accumulation of pollutants of varying range in the aquatic ecosystem negatively impacts the well-being of individuals and the surrounding environment. Information pertaining to different pollutants and their sources are summarized as under:

Pollutants from industries

Industries are recognized as the backbone of the country's economic progress (Ma 2023). In the last few decades, rapid industrialization has led to different aspects of contamination of soil and water resources. Considered as a by-product of increased industrialization, pollution of the waterbodies has been observed to have a dramatic impact on environmental degradation (Omri and Bélad 2021; Wang et al. 2021). Besides having a huge impact on the scarcity of water and its depletion from natural sources, release of the sewage, if discharged in an untreated way, contributes significantly to eutrophication of the water bodies and progresses to genotoxicity among different life forms that inhabit water bodies (direct effect) or on other life forms after undergoing bioaccumulation in the food chain (indirect effect) (Patel et al. 2019). The main source of pollutants is distilleries, tanneries, pulp and paper, textiles, and dye-manufacturing units.

Distillery industry

Distillery sector is considered as the economic driver in developing nations (Tripathi et al. 2021). Irrespective of their economic benefits, distillaries contribute significantly to the pollution of the environment via, release of substances (both organic and inorganic) as part of the waste (Kumar and Chandra 2020a, b; Tripathi et al. 2022). Distilleries involved in the production of molasses generate around 15 l of wastewater for every liter of the alcohol produced (Mikucka and Zielińska 2020). Production of organic chemicals in a fermentation reaction generates around 55–60% waste of highly complex composition and sludge (Valentino et al. 2019). Distillery wastewater (DWW) contains a larger proportion of organic (polysaccharides, phenolic compounds, fungicides, fatty acids, etc.) and inorganic compounds (heavy metals, mineral ions, and others); some of them are well-known for their role as endocrine disruptors (EDCs) (Caizán-Juanarena et al. 2020). DWW poses threat to both aquatic (damaging aquatic flora and fauna) and terrestrial (decreasing soil fertility by decreasing dissolved oxygen and availability of minerals like Mn) ecosystems, besides exerting a detrimental effect on human health (Campanale et al. 2020).

Tannery industry

Tannery, believed to contribute ~ 40% of the world's chromium pollution, is considered as one of the most polluting industries in the world (Bień et al. 2017). With a problem of low productivity (attributable to ineffective and unsustainable tanning procedures), excessive use of water and chemicals in the tanning led to the production of high load of pollutants harmful to environment and humans of discharge from the industry (Joseph and Nithya 2009). The use of excess water in tanning that is needed for chemicals to penetrate into the three-dimensional skin/hide matrix led to the production of around 145 billion gallons of effluent annually (Sathish et al. 2016). As only 65–75% of chemicals undergo absorption in the process, a huge amount left unused is subsequently discharged as effluent from the tannery unit. The wastewater not only degrades the quality of underground water in the nearby vicinity, but also produces significant impact on the agricultural productivity (Dixit et al. 2015; Haydar et al. 2015). Of the two forms of chromium, trivalent chromium (Cr^{3+}) salt-based tanning led to the production of leather with high hydrothermal stability, superior dyeing properties, and suppleness in a time-efficient manner (Kanagaraj et al. 2008). Effluents (both solid and liquid) released from the tannery unit that disturb carbon to nitrogen ratio require the use of sophisticated procedures to achieve its removal from the environment (Saikia et al. 2017). Besides rendering the enzymes inactive, effluent rich in nitrogen promotes eutrophication that renders water unfit for use (Wang et al. 2018).

Pulp and paper industries

The pulp and paper industry (PPI, sixth larger polluter in the world) that makes excessive use of water generates huge mass of wastes (solid, liquid, and gaseous) (Uğurlu et al. 2008). Recalcitrant lignin, tannins, and resins produced as black liquor contributes to 10–15% of the effluent generated as part of waste water and a total of 90–95% of the total pollution load in water bodies (Chandra et al. 2011). Around 50–60% of lignocellulosic waste is released as part of pulping, bleaching, and other parameters in the manufacturing of paper (Dwivedi et al. 2010). The use of chlorine dioxide as elemental chemical in pulp and paper industries led to its discharge in environment, where it reacts with organic matter and generates organo-chlorine compounds that are considered potent for their reproductive and genetics observed among aquatic and terrestrial animals (Dwivedi et al. 2010). Creation of scum and slime layer at the water surface alters its pH, BOD, and COD, thereby exerting harmful effects on aquatic life and endangers life of terrestrial ones including humans (Kumar and Sharma 2019).

Textile and dye industries

Dominating the economies of nations like India, Pakistan, and Bangladesh, textile industries (TIs) serve as one of the major sources of environmental pollution (Ceretta et al. 2020). The usage of water and synthetic chemicals in the production process of textiles causes release of effluents containing a significant proportion of persistent coloring pollutants (PCPs) into aquatic water bodies (Bharagava et al. 2018; Kumar et al. 2020). As TIs make use of a variety of fibers both synthetic (polyster, nylon, viscose, etc.) and natural (cotton, jute, wool, etc.), a lot of toxic substances found their usage at different stages (including sizing, softening, anti-creasing, and finishing), in the manufacturing of textiles (Rosa et al. 2020; Sun et al. 2020). Of the 7×10^7 t of dyes manufactured annually, 10,000 t of them are used in TIs alone (Chandanshive et al. 2020). In the dying process, a variety of synthetic dyes such as azo, vat, acidic, basic, and sulfide are used, which if undergoes partial detachment from the fibre, are released into the water bodies (Asgari et al. 2020). Due to poor degradability of synthetic dyes, they exert effects such as change in pH, COD, and BOD, besides having a direct impact on the aquatic life (Yaseen and Scholz 2019). As manufacturing of the pigment makes use of heavy metals, a lot of them such as mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), and lead (Pb) are discharged as part of textile industry-based waste into the environment (Kumar et al. 2020; Rosa et al. 2020; Chandanshive et al. 2020). Additionally, TIWW also contains a good proportion of salts, volatile organic compounds (VODs), dispersants, surfactants, reducing agents, detergents, and others (Yuan et al. 2020). Dumping of effluents generated in the textile units along with wastewater that are directly discharged into drains, canals, and rivers or feed into the sea as in the case of textile units set up at Kanpur, India, is emptied into Bay of Bengal (Bharagava et al. 2018), imposes serious complications within the living system and poses serious risks to life and a significant reduction in soil fertility (Xue et al. 2019).

Agrochemicals as pollutants

The ever-increasing need for food required to sustain the survival of humans and other life forms relies on the agriculture (Sadowski and Baer-Nawrocka 2018). In the agricultural practices, plants require nutrients (both organic and mineral) to cope up with the overall growth and development and as such to their productivity (Wawrzynska and Sirko 2014). Considering their importance to plant growth and development, it was observed that farmers progressively became dependent on the use of chemicals (fertilizers, pesticides, etc.) to fulfill their requirement in the soil towards achieving agricultural sustainability via improvement in the quality and yield of different crops (Bhat et al. 2023). However, the use of pesticides, fertilizers, and others in agricultural practices contributes significantly to contamination of soil and water resources (Stoyanova and Harizanova 2019). The use of chemical pesticides and fertilizers was found having severe ecological and economic implications and serious health concerns at the global scale that putforth the need of reducing their use in the agricultural practices. The following section summarizes the contribution of chemical pesticides and fertilizers to the pollution of aquatic water bodies.

Pesticides

The use of pesticides to manage pests and weeds and improve food production is one of the demanding procedures involved in agriculture (Allettoet al. 2010). Pesticides are widely employed owing of their efficiency and the consequent rise in the demand for enhancement in the agricultural food productivity (Carvalho 2006). Of the different pesticides such as phorate, chlorpyriphos, methyl parathione, endosulfan, hexachlorocyclohexane, and dichlorodiphenyltrichloroethane (DDT), the latter two, i.e., hexachlorocyclohexane and DDT, account for 67% of the total pesticide use in agriculture in the Asian subcontinent (Köck-Schulmeyer et al. 2013). Their property to vaporize makes them infiltrate into the soil, flow into rivers, and travel great distances before having an impact on the ecosystem. They enter the water ecosystems through runoff from the application site, drift from spraying, precipitation washing down, and direct dusting and spraying of pesticides in low-lying areas. These pollutants undergo bioaccumulation over the span of time, thereby results in great damage to flora and fauna exhibiting the natural water bodies (Gani and Kazmi 2017).

Fertilizers

Fertilizers are chemical compounds that are employed in agriculture to boost crop productivity. The use of nitrogenous fertilizers in agriculture is followed by nitrate leaching as observed in some dry and semiarid regions. As the majority of the nitrogenous fertilizers are not absorbable, they reach the aquatic environment through three separate channels, drainage, leaching, and flow, and as such serve as the potential sources of pollution in the aquatic ecosystem. Even in ideal circumstances, it has been observed that plant is able to utilize only 50% amount of the nitrogenous fertilizers added to the soil; the remaining amount undergoes evaporation of which a significant proportion (15–25%) reacts with soil organic matter and 2–10% induce direct effect following contamination of surface and groundwater resources (Singh 2018).

Pharmaceutical compounds as pollutants

Though the term pharmaceuticals are used for substances that are used to treat, reverse, and prevent illnesses, it has been broadened to include even veterinary substances and also applies to illegal narcotics (Daughton 2003). It has been estimated that thousands of tons of human pharmaceuticals including antibiotics, anti-inflammatory substances, and synthetic hormones are created and used each (Boxall 2004). The sources of pharmaceutical contaminants in water are hospitals, farms, household and commercial garbage, and industrial operations (Table 1). On accomplishing the mission of treating a disease in the target organisms, they enter the aquatic ecosystem either as a parent compound or as their metabolite product on excretion from the system through feces and/or in the urine (Ratnasari et al. 2022). Simultaneously, it has lately been demonstrated that many of these substances from the manufacturing units do not undergo biodegradation after conventional treatment and as such persists following dumping into water bodies together with treated effluent. Studies have reported that wastewaters getting effluents treated in conventional manner contains pharmaceuticals in the concentration range of ng L^{-1} to µg L^{-1} (8–11). In the conventional treatment approaches, inconsistent or poor removal has been reported for diclofenac (3–70%), carbamazepine (< 16%), and clofibric acid (< 35%) (Gagnon and Lajeunesse 2008; Kosjek et al. 2009; Santos et al. 2010). Pharmaceuticals can accrue in a range of trophic level species, including humans, or through biomagnification in the dietary items owing to their hydrophobic and resilient characteristics. These may alter microbial populations, inhibit microbial performance and growth, and affect the pace at which bacteria remove nitrogen from the environment (Xiong et al. 2018). The monitoring of pharmaceuticals in the environment is a difficult task as veterinary products outflow directly into aquatic systems as part of manure or through direct application in the aquaculture (Rivera-Utrilla et al. 2013).

Pollutants from household activities

The household wastes contain detergents which constitute ~ 5–20% of the phosphate found in groundwater. The problems caused by detergents are attributed to their nonbiodegradability by virtue of which they cause aquatic toxicity and act as potent endocrine disruptors (Patel et al. 2019). There are certain compounds in detergents that in combination with other substances liberate fumes, thereby affecting the eyes and causing serious damage to the mucous membrane that leads to respiratory failure (Slack et al. 2004). The electric and electronic devices used in houses when left as such without proper disposal often contaminate the environment (Rani et al. 2013). The majority of the domestic sewage that is dumped into the water bodies such as river is untreated (Gambhir et al. 2012). It makes water unfit for drinking and consumption for other purposes. Domestic sewage contains toxic substances, solid waste, plastic litter, and bacterial contaminants, all of which contaminate water (Bashir et al. 2020).

Environmental and health effects of pollutants

Irrespective of the cost and consequences, the release of pollutants into the environment has created havoc that continuously threatens human health and equally jeopardizes sustainability of the modern societies (Fuller et al. 2022). Considering the data of the Global Burden of Diseases, Injuries and Risk Factor study (GBD 2023), it was found that pollution is an entity attributed to an economic loss of about US\$4.6 trillion (6.2% of the global economic output) and 9 million deaths (~ 16% of the global deaths),

Table 1 Table summarizing the level of pharmaceutical pollutants in water bodies along with their detection methods across the globe

S. no	Compounds	Sample	Conc. (mg L^{-1})	Detection method	Country	References
1	Levofloxacin	Water (river, public supply wells, fresh water creep, Municipal effluent, Drinking water)	10	Gas chromatography	India	Gao et al. (2019)
2	Ofloxacin		0.6	Nanofiltration	Italy	Zuccato et al. (2005)
3	Tetracycline		0.3	Ultrafiltration	Italy	Panthi et al. (2019)
4	Trimethoprim		0.16	Liquid chromatography	Vietnam	Hoa et al. (2011)
5	Atenolol		0.08	Nanofiltration	United States	Schaider et al. (2014)
6	Ifosamide		0.0005	SCF	Switzerland	Buerge et al. (2009)
7	Metoprolol		0.15	SCF	France	Gogoi et al. (2018)
8	Carbamazepine		0.06	SCF	United States	Glassmeyer et al. (2017)
9	Bisphenol A		10	SCF	Spain	Riva et al. (2018)
10	Ibuprofen		0.5		Kenya	Sharma et al. (2019)
11	Triclosan		0.1	SCF	Brazil	Riva et al. (2018)
12	Naproxen		0.8	Tandem mass spectroscopy	India	Sharma et al. (2019), Agüera et al. (2013)
13	Diclofenac		0.01	Mass spectrophotometer	Kenya	Phasuphan et al. 2019
14	Norfloxacin		0.5	Liquid chromatography	India	De Souza et al. (2020a, b), Wu et al. (2010)
15	Paracetamol		0.01	Liquid chromatography	Kenya	K'oreje et al. (2021)
16	Atrazine		0.17	Mass spectrophotometer	Brazil	Sposito et al. (2018), Lebedev et al. (2020)
17	Diuron		0.23	SCF	Spain	Brumovský et al. (2017)
18	Fipronil		0.29	SCF	Brazil	Sposito et al. (2018)
19	Quinalphos		0.64		Malayasia	Wee et al. (2016)
20	Galaxolide		0.10	SCF	United States	Glassmeyer et al. (2017)
21	Paraben		0.03		Spain	Pico et al. (2019)
22	Dibutyl phthalate		0.16	SCF	Taiwan	Gou et al. (2016)
23	Perfluorobutanoic acid		0.14		United States	Pico et al. (2019)
24	Ethinyl estradiol		0.03	SCF	China	Li et al. (2015)
25	Estrone		0.02	SCF	United States	Glassmeyer et al. (2017)

with the major effect observed in low-income and middle-income countries (LMICs) (Andrigan et al. 2018). It seems imperative that economic prosperity carries the burden of sacrificing the environment and compromising the human health (Khan et al. 2021; Borhan et al. 2021). Considering pollution as a planetary threat, it is noteworthy that its effects on health transcend local boundaries and as such require framing of environmental problems at a global scale towards welfare of the residents (Fuller et al. 2022; Ma 2023). Facing with such a dilemma, it becomes inevitable that safeguarding the environment requires elimination of the outdated production capacity associated with the major problem of environmental pollution.

As environmental pollution problems are often interconnected with the loss of biodiversity, efforts are made to control the pollution and as such prevent the occurrence of the pollution related diseases (Fuller et al. 2022). The wastes discharged as effluents from different point sources undergo various biological and chemical transformations with the production of hazardous by-products that exert harmful effects on both the aquatic as well as on terrestrial system (Fig. 1).

Effects of pollutants on the environment

Industrial discharge having a large proportion of organic and inorganic components exerts a direct effect on the life of aquatic organisms via interference in the photosynthetic procedure or metabolic machinery (Table 2). Pollution of the water bodies results in the enhancement of the contaminants, mostly organic materials, which raises the BOD and COD parameters. As aquatic ecosystems are impacted irreversibly, it puts both animal and plant species at risk (Li et al. 2019). The chemical compounds such as fertilizers, pesticides, and ammonia, accumulates over time and undergo bioaccumulation at different steps of the food chain. Having a detrimental effect on the life of aquatic organisms, exposure to chemical compounds significantly decreases their number to a larger extent (Sharma and Bhattacharya 2017). Additionally, a pattern of industrial discharge into water bodies inevitably

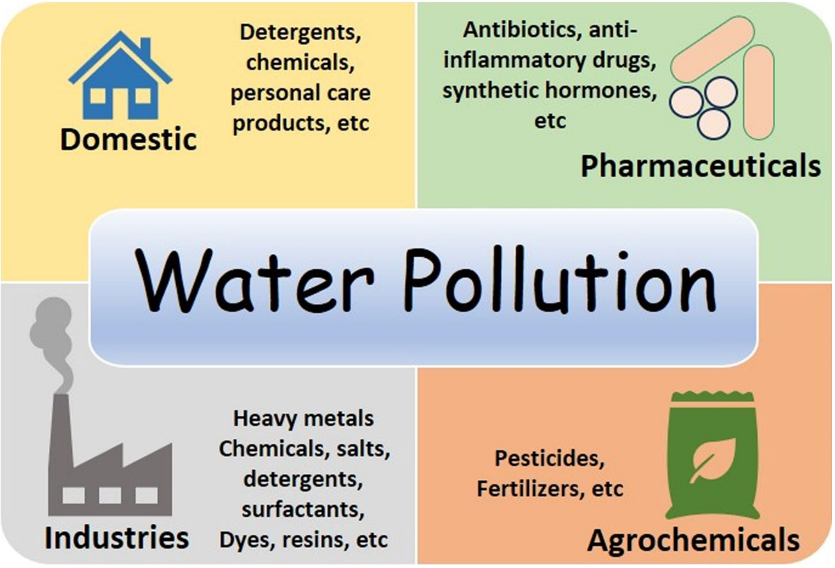

Fig. 1 Sources of contaminants and their effect of various life forms

exposes benthic microorganisms to these harmful pollutants (Amelia et al. 2021). The release of heavy metals as part of discharge into water bodies not only alters its physical and chemical composition but also causes disturbance in the biological parameters such as composition, diversity, and community structure of the population (Zamora-Ledezma et al. 2021). Fish's respiratory systems are impacted by heavy metals, particularly iron. When these fish are consumed by other species, the iron clog in their gills makes them fatal (Slaninova et al. 2014). Direct discharge of untreated or partially treated textile industry wastewater (TIWW) having different compositions of unused dyes exerts a direct effect on aquatic life via reduction in the penetration of sunlight (reduced photosynthetic activity), and in creating anoxic environment through reduction in the dissolved oxygen levels (Ceretta et al. 2020). Having a higher proportion of toxic compounds, it exerts different effects ranging from cytotoxicity to mutagenicity and carcinogenic effect on the life it holds (Ceretta et al. 2020; Rahim and Mostafa 2021). A large number of effects particularly sexual immaturity, reduction in gonad size, and rate of reproduction were found associated with the waste discharge from the paper and pulp industry (Rahim and Mostafa 2021). Additionally, a large number of complications such as ecotoxicity and sluggish regeneration of gills in Caddis larvae were observed as long-term effects of waste discharge from the pulp and paperboard industry (Ratia et al. 2012). Similarly, in another study, the presence of resin acid and retene was found to have a dramatic effect in exerting genotoxicity in sea bass followed by reduction in the activity of ethoxyresorufin-O-demethylase in the liver (Mearns et al. 2015).

The unabated use of various chemicals followed by their unplanned and unregulated release into the environment results in their pollution of the terrestrial environment (Fig. 2), thereby exerting a profound effect on the life of both flora and fauna in the terrestrial settings. If the plants are irrigated by wastewater having a low level of pollutants, it serves a good purpose of promoting plant growth as part of sustainable agricultural practice; however, in the case of high pollutant levels, it was found to exert serious growth-related effects in plants (Khalid et al. 2018). The soil surface affected by irrigation of the contaminated water having a substantial amount of both organic and inorganic substances results in pronounced effect on the overall development of plants. Effluents from industrial settings having a high load of heavy metals hamper seed germination, growth and development, and yield of crop plants (Chandra et al. 2011).

Effects of pollutants on human health

Pollutants such as heavy metals, pesticides, and industrial chemicals have profound and detrimental effects on human health. These include neurotoxicity, nephrotoxicity, and even long-term impacts on the heart, reproductive, and endocrine systems, and can cause various cancers and respiratory system-related disorders. Extensive research has been conducted on the toxicity resulting from their exposure, as documented below:

Pollutants in ROS/RNS production

Pollutants in particular heavy metals have the capacity to generate extremely reactive molecules like free radicals, leading to the oxidation of protein sulfhydryl groups, protein depletion, DNA impairment, and lipid peroxidation. The toxicity predominantly results from the generation of reactive oxygen species (ROS) and reactive nitrogen species (RNS), which interfere with the cellular

Table 2 Table summarizing the contaminant type, source, and their effect on different forms of life along with remediation strategies

Contaminant	Source	Effect on animals	Effect on plants	Remediation	Reference
Lead (Pb)	Pesticides, industries, vehicular emission	It damages the renal and nervous systems and also causes cancer It also causes mental retardation, autism, psychosis	It inhibits photosynthesis, the germination of seeds and retards growth of seedlings It also decreases germination percent, germination index, root/shoot length and dry mass of roots and shoots	Precipitation stabilization, ion exchange, and adsorption	Vareda et al. (2019), Pratush et al. (2018), Guerra et al. (2012), Fu and Wang (2011), Martin and Griswold (2009)
Mercury (Hg)	Pulp and paper industries, fossil fuel combustion and plastic industries	It damages the nervous system, reproductive system, and respiratory system. It adversely effects on kidneys Changes in lipid metabolism, cellular transport, effect on gene expression and effect the growth and characteristics of plasma and blood	In plants, it binds to sulfydryl/thiol groups of proteins and forms S-Hgs. Hg toxicity in plants occurs via its binding to SH groups of proteins, displacement of essential elements, and disruption of protein structure	Coagulation, activated carbon and reverse osmosis	Joseph et al. (2019), Vareda et al. (2019), Fu and Wang (2011), Bridges and Zalups (2010)
Cadmium (Cd)	Industries (electroplating and metallurgical), insecticides, petroleum products and synthetic chemicals	It causes lung and liver toxicity and has adverse effect on reproductive system	It has negative effects on the growth of the plant and toxic effects are seen both at morphological and physiological levels	Electrodialysis, reverse osmosis and softener	Vareda et al. (2019), Guerra et al. (2012)
Arsenic (As)	Industrial waste water, municipal wastewater, pesticides and sewage sludge	It damages the skin and causes circulatory system problems. It also increases the chances of getting cancer	In high concentration it inhibits photosynthesis by decreasing the photosynthetic pigments concentration and damaging the chloroplast	Oxidation, Coagulation-floculation, and membrane techniques	Joseph et al. (2019), Vareda et al. (2019)
Chromium (Cr)	Various industries like leather, tanning, textile and electroplating. It is also released by industrial sewage and anticorrosive products	It causes skin inflammation, ulcer, pulmonary congestion and vomiting. It also damages kidney and liver	Adversely impact the metabolic processes in plants and reduces the growth and productivity of crops It induces phytotoxicity Effects on hormonal imbalance Inhibited root and shoot growth and seedling length with the increasing of chromium concentration	Electrocoagulation, ion exchange, chemical precipitation, and membrane separation	Vareda et al. (2019), Pratush et al. (2018)

Table 2 (continued)

Contaminant	Source	Effect on animals	Effect on plants	Remediation	Reference
Copper (Cu)	Steel, electroplating, metallurgy and mining industries. Pesticides and fertilizers	It causes anaemia, hair loss and headache	Effects the photosynthesis of the plant and damages the roots of the plant Iron chlorosise happened in plant leaves due to its high concentration	Ultrafiltration, Nanofiltration and reverse osmosis	Vareda et al. (2019), Pratush et al. (2018)
Fluoride	Textile and plastic industries	Dental and skeletal fluorosis, gastrointestinal disorders, infertility	Strongly inhibited photosynthesis and other processes Its accumulation can cause nacrosis on the upper edge of the leaves and progress to the leaf base It affects early stage or pigment synthesis and degradation of chloroplast	Adsorption, precipitation, and ion exchange	Chowdhary et al. (2020a, b)
Nitrate	Industrial wastewater, nitrate based fertilizers	Methemoglobinemia in infants, oral and gastrointestinal cancers. Vascular dementia, absorption and secretive functional disorders of the intestine and neural tube defects		Ion-exchange, reverse osmosis and electodialysis	Chowdhary et al. (2020a, b)
Dyes(methyl nitro, orange, remazol, methylene blue, malachite green reactive dyes etc.)	Industrial effluents from painting, textile, paper, printing and tanning industries and from transportation oil spills	Dyes are mutagenic, carcinogenic and causes organ dysfunction Respiratory distress, digestive and mental disorders in humans Inhibit the activity of gonadotropic cells in pituitary gland	Reducing light penetration through water decreasing photosynthetic activity, causing oxygen deficiency and deregulate the biological cycles of aquatic biota	Oxidation, adsorption, and flocculation-precipitation	Saravanan et al. (2021), Khan et al. (2022), Srivastava et al. (2004)
Chlorinated solvents e.g., Trichloroethane(TCE)	Textile, electronic and plastic industries	It affects central nervous system, liver and kidneys It also depletes the ozone layer			Kishor et al. (2021)
Carbon disulfide	Industrial effluents from painting, textile, plastic	Sexual and gastrointestinal disorders, birth defects, reproductive toxicity, chronic skin conditions, kidney diseases and leukaemia			Kishor et al. (2021)

Table 2 (continued)

Contaminant	Source	Effect on animals	Effect on plants	Remediation	Reference
Formaldehyde	Textile, electronic and plastic industrial effluents	Human carcinogenic as per IARC, National Cancer Institute (NCI) and US Environmental Protection Agency (EPA), allergies, skin irritant, dermatitis, irritate mucous membranes and the respiratory problems	Due to its presence reduction in plant wet weight and water content takes place	Activated hydrogen peroxide or ozone	Kishor et al. (2021)
Chlorophenols (e.g., pentachlorophenol (PCP)	Industrial effluents (textile, plastic, rubber, plastic etc.)	Affects the immune, cardiovascular and nervous system It also affects kidneys, blood, liver, eyes and cause dermatitis Carcinogenic in nature	–	–	Kishor et al. (2021)
Alkylphenols, nonylphenol ethoxylates (NPEs), and nonylphenols (NPs)	Textile, electronic and plastic industrial effluents	It is highly toxic to aquatic life and disrupts endocrine system in animals It increases incidence of breast cancer abnormal growth patterns and neurodevelopmental delays in children	–	–	Kishor et al. (2021)
Phthalates (DINP: di-isononyl phthalate and, BBP: butyl benzyl phthalate)	Textile and plastic industerial effluents	Carcinogenic, endocrine disrupters and aquatic toxicant It affects reproductive system and impair fertility	–	–	Kishor et al. (2021)
Oils	Transpotation oil spills and industerial effluents	Respiratory, carcinogenic and neurological problems. Also causes nose and eyes irritation	Oil does not only impede the growth of plants, it creates further damage by leading to algae formation. Sometimes, oil in water results into increase in algae which grows very quickly. The widespread algae population in water creates adverse conditions for the growth of other aquatic plants	Gravity sedimentation, demulsification, membrane separation and biological treatment	Saravanan et al. (2021)
Plastics	Disposal of packaging material and industrial wastes into oceans	Liver dysfunction, lung problems, deafness, impaired immune function	It causes alteration of cell membrane and generation of oxidative stress	Reverse osmosis, filters	Saravanan et al. (2021)

Table 2 (continued)

Contaminant	Source	Effect on animals	Effect on plants	Remediation	Reference
Pesticides and herbicides (chlordecone, glyphosate, DDT, atrazine)	Agricultural practices	Disruption of endocrine system and impairment of organs, reproductive toxicity in animals, neurological disorders, reduction in erythrocyte and leucocyte, malformation like spinal curvature problems and pericardial edema	Causes oxidative stress by producing reactive oxygen species and finally leads to retarded growth and photosynthetic efficiency of plants	Reverse osmosis with activated carbon filters	Saravanan et al. (2021), Multigner et al. (2016), Kao et al. (2019)
Pathogenic microorganisms	Domestic discharge, sewage and hospital wastes	Adversely effects human metabolism	They cause leaf spots and blights, soft rots of fruits, roots, and storage organs, wilts, overgrowths, scabs, and cankers	UV disinfection, chlorine and ozonation	Saravanan et al. (2021)
Naproxen	Pharmaceutical industries, hospital effluents, biosolids and water reuse	Increase the risk of heart disease	Enhanced formation of ROS, lipid peroxidation, loss of plasma membrane integrity, and changes redox and antioxidant system	Ionic-liquid-based systems	Ortúzar et al. (2022)
Ibuprofen	Animal and human excretion, pharmaceutical improper disposal, and livestock treatment	Affects aquatic life adversely It alters the growth rate and reproductive system It inhibits cell division and non-disjunction of chromosomes to several pairs	It inhibits the photosynthesis of some plants and its significantinfluence on early root development	Biofilm reactors are used for degradation with activated sludge	Chopra and Kumar (2020)
Diclofenac	Animal and human excretion, pharmaceutical improper disposal, and livestock treatment	The inhibition of prostaglandin E2 synthesis Osmoregulation disruption of mussels It affects the enzymatic activities (catalase, superoxidedismutase) Genotoxic effects leading to DNA damage in *Mytilus* spp.	It inhibits the photosynthesis of some plants and retards the root growth of plants	Biosorption and advanced oxidation techniques	Ortúzar et al. (2022)
Acetaminophen	Pharmaceutical industry	Dysplacia	Retards the growth of plants	Biofilm reactors are used for degradation with activated sludge	Galus et al. (2013)

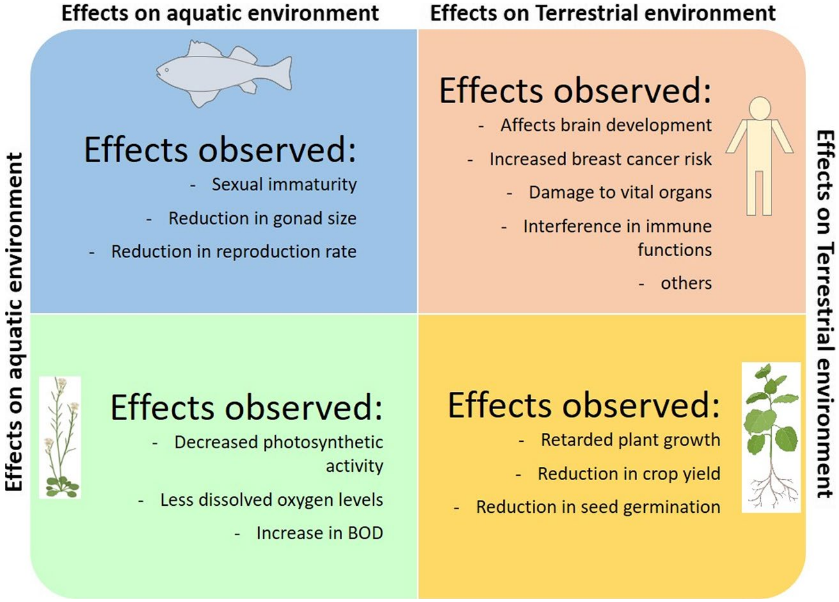

Fig. 2 Effects of pollutants on aquatic and terrestrial environment

redox processes (Jan et al. 2011, 2015). ROS, recognized for their remarkable chemical reactivity, encompasses uncharged molecules such as hydroxyl ($OH^•$), peroxyl ($RO_2^•$), superoxide ($O_2^{•-}$), and alkoxyl ($RO^•$), along with distinct non-radicals like hydrogen peroxide (H_2O_2) and peroxynitrite ($ONOO^-$). These species can function as oxidizing agents or can readily convert into radicals. The intracellular production of superoxide anion ($O_2^{•-}$) predominantly occurs through non-enzymatic routes involving redox constituents such as semi-ubiquinone (a constituent of the mitochondrial electron transport chain) (Mathew et al. 2011; Flora et al. 2012; Brochin et al. 2008; Mishra et al. 2021). Alternatively, enzymatic pathways, including xanthine oxidase, NADPH-oxidase (NOX), or auto-oxidation reactions, also contribute to superoxide anion generation (Andrés et al. 2023). Superoxide anion ($O_2^{•-}$) displays limited reactivity under physiological conditions and demonstrates poor membrane permeability. When encountering nitric oxide (NO), their interaction gives rise to the creation of peroxynitrite ($ONOO^-$), which subsequently transforms superoxide into exceptionally reactive intermediates like the hydroxyl radical ($^•OH$), known for its extremely brief half-life (Li et al. 2022). The genesis of nitric oxide is facilitated by nitric oxide synthase isozymes, encompassing mitochondrial nitric oxide synthase (mtNOS) and endothelial nitric oxide synthase (eNOS) which catalyze the conversion of L-arginine into citrulline. Nitric oxide has demonstrated enhanced stability within environments characterized by limited oxygen availability. Given its amphipathic properties, $NO^•$ readily traverses cytoplasmic and plasma membranes. Upon interaction with superoxide anion, NO leads to the formation of peroxynitrite ($ONOO^-$) (Szabó et al. 2007).

Perturbations in the balance of ROS/RNS generation or the decline in ROS-scavenging capability resulting from external stimuli have been observed to induce changes in cellular functions. These alterations can manifest through direct modifications of biomolecules and/or by aberrant activation or inhibition of specific signaling pathways, subsequently exerting an impact on growth factor receptors. The interaction of external metals with protein ligands, resulting in the displacement of natural physiological metals from their carriers, leads to the disturbance of cellular physiology (Jan et al. 2015; Li et al. 2022). The binding of metal cations to unintended ligands, causing structural rearrangements, also disrupts the regular functionality of cellular proteins. Of particular significance are the hydroxyl ($^•OH$) radicals produced by the Fenton reaction, in addition to the potent oxidizing agent peroxynitrite ($ONOO^-$), which subsequently gives rise to nitrite ($^•NO_2$) and hydroxyl ions, contributing to the disruption of normal cellular processes.

$$Fe^{2+o} + H_2O_2 \rightarrow Fe^{3+o} + {}^{o•}OH + OH^-$$

These reactive species are commonly involved in the modification of proteins. The impairment of proteins by diverse metal ions primarily entails the deterioration of histidine residues, attachment of carbonyl groups, and the formation of bityrosine cross-links. Additionally, the process involves the generation of carbon-centered alkoxyl ($RO^•$) radicals, peroxyl ($ROO^•$) radicals, and alkyl radicals ($R^•$) (Demirci-Cekic et al. 2022).

Heavy metals in nephrotoxicity

Nephrotoxicity is a term used to describe the toxic or harmful effects on the kidneys caused by pollutants present above the permissible limit prescribed by different agencies (Table 3). These substances often referred to as nephrotoxins

Table 3 Permissible limit of heavy metals in aquatic systems and their concentration observed in the humans

Heavy metal	WHO value (mg L^{-1})	EPA value	Indian standards	Blood (μg L^{-1})	Hair
Arsenic	0.01	0.05	0.05	0.046	0.014
Lead	0.01	0.05	0.1	0.010	0.018
Mercury	0.001	0.002	0.001	1.10	0.020
Cadmium	0.003	0.005	0.01	0.70	0.21
Chromium	0.05	0.05	0.05	0.391	0.239
Copper	2.0	0.3	0.2		
Nickel	0.02	0.1	0.05		
Reference	Kumar et al. (2023)	Gautam et al. (2016)	Gautam et al. (2016)	Smith et al. (2006), Reuben et al. (2020), Pollack et al. (2015), Mokhtar et al. (2002)	Chung et al. (2015), Den Hond et al. (2011), Katiyar et al. (2009)

exhibit a non-uniform distribution pattern, primarily within the kidneys, resulting in the onset of acute renal failure.

Mercury (Hg) Demonstration of escalating nephrotoxicity severity in relation to both dosage and duration, encompassing damage to proximal and distal tubules, glomerular membrane impairment, brush border membrane loss, and instances of necrosis. The assessment of their influence on renal function is typically conducted through two approaches: evaluation of glomerular function, predominantly determined by the presence of high molecular weight proteins like albumin and transferrin, or examination of tubular function, assessed using low molecular weight proteins such as β2-microglobulin (β2-MG), retinol-binding protein (RBP), and α1-microglobulin (α1-MG) present in urine (Langworth et al. 1992; Franko et al. 2005). The interaction between mercury and sulfhydryl groups leads to the disturbance of tubular enzymes like *N*-acetyl-β-D-glucosaminidase (NAG), impacting their functionality. This disruption of sulfhydryl-containing enzymes is employed in the evaluation of renal tubular function (Al-Saleh and Elkhatib 2012). A study exploring the potential of serum creatinine and blood urea nitrogen levels as markers to estimate renal function and evaluates the nephrotoxic impacts stemming from mercury exposure (Sedky and Famurewa 2023). Upon analyzing the binding affinities with different compounds, it becomes clear that inorganic mercury shows stronger affinity towards endogenous thiol-containing molecules such as glutathione and cysteine, in contrast to ligands containing oxygen and nitrogen (Itterheimová et al. 2023). Tubular microdissection investigations have revealed that the uptake and subsequent accumulation of inorganic mercury in the kidneys primarily transpire within the convoluted and straight segments of the proximal tubule (Han et al. 2022). Evidence supports the notion that mercury-thiol conjugates, specifically glutathione, play a pivotal role in facilitating the uptake of mercury within the proximal tubules of the kidneys. In terms of this uptake process, research indicates the participation of distinct transporters that operate separately at both the luminal and basolateral membranes (Jan et al. 2015). Considering the presence of mercuric glutathione conjugates in the tubular lumen and the interrelation between γ-glutamyltransferase (γ-GT) activity and the luminal absorption of mercuric ions by proximal tubular cells, the plausibility arises for the transportation of γ-GT activity-derived compounds, including the mercuric conjugate of cysteinylglycine. Nonetheless, the presence of membrane-bound dehydropeptidases (e.g., cysteinyl glycinase) contributes to a relatively low rate of transport.

Cadmium (Cd) The kidney's vulnerability to cadmium was first recognized in a preliminary investigation that encompassed individuals who had encountered cadmium oxide dust and emissions within a nickel–cadmium battery production plant (Hayat et al. 2019). These individuals demonstrated a significant incidence of compromised renal function, marked by proteinuria and reduced glomerular filtration rate. Subsequent studies targeting cadmium-exposed workers have consistently reported various renal consequences. Analogous indications of renal impairment have been documented across a range of additional studies involving individuals with occupational exposure to cadmium (Scammell et al. 2019). Prolonged exposure to elevated cadmium concentrations can lead to glomerular damage, which consequently leads to reductions in glomerular filtration rate (GFR) (Satarug et al. 2022), a correlation between blood cadmium levels and glomerular filtration rate (GFR) was established among workers exposed to cadmium. *Arsenic (As).* An investigation employing a cross-sectional design evaluated renal function indicators in glass factory workers with exposure to arsenic (specific concentrations undisclosed). The study revealed no significant distinctions in urinary levels of various proteins (including albumin, β2-microglobulin, retinol-binding protein, and brush-border antigen), commonly utilized as markers of glomerular impairment or tubular cell exfoliation, when compared to control (Saracci et al. 2019).

Chromium (Cr) Renal function analyses have been conducted on individuals engaged in diverse professions such as chromate and dichromate manufacturing, ferrochromium production, boilermaking, chrome plating, stainless steel welding, and alloy steel plant operations. Particularly noteworthy are the findings from individuals exposed to chromium (VI) compounds in a chromate production setting, where comparatives with control groups revealed heightened urinary concentrations of retinol-binding protein and brush border protein antigen (Sankhla and Kumar 2019). An analogous investigation was executed on a cohort of 43 male laborers within the chromate and dichromate production sector. The range of occupational exposures of chromium (VI) was 0.05 to 1.0 mg m^{-3} in the form of chromium trioxide, and the average tenure of employment was 7 years. Individuals with urinary chromium g^{-1} creatinine levels exceeding 15 µg exhibited heightened excretion of tubular antigens in their urine and retinol-binding protein (Zheng et al. 2020). The researchers propose that identifying low molecular weight proteins, like retinol-binding proteins or antigens, in urine could potentially function as early signs of renal dysfunction.

Copper (Cu) Several instances of renal toxicity have been documented in case reports after the accidental and intentional consumption of copper sulfate. The prevailing outcomes frequently encompass heightened levels of serum creatinine, hemoglobinuria, oliguria, and the presence of hematuria (blood in the urine) (Du and Mou 2019; Gupta et al. 2018; Lubica et al. 2017; Yadla et al. 2015; Gamakaranage et al. 2011; Malik and Mansur 2011). In certain instances, cases of renal failure were documented alongside other indications of copper toxicity; however, comprehensive specifics regarding the precise nature of the renal impacts were not elucidated (Valsami et al. 2012; Griswold et al. 2017; Gunay et al. 2006). In conjunction with oliguria and hemoglobinuria, a male individual aged 40 exhibited the emergence of ketonuria and proteinuria after purposeful consumption of copper-8-hydroxyquinolate. Similarly, a female aged 19, who deliberately ingested a pesticide containing copper oxychloride, experienced the development of chronic renal failure (Gunay et al. 2006). In a study, four individuals who consumed a fatal dose of copper sulfate exhibited glomerular congestion and tubular cell denudation. Furthermore, out of 125 individuals intentionally ingesting substantial quantities of copper sulfate, five cases were documented with acute renal failure (de Carvalho Machado and Dinis-Oliveira 2023). *Lead (Pb).* Reduced glomerular filtration rate (GFR), presence of proteinuria, enzymuria, compromised tubular transport, and observable histopathological impairments. It causes renal system damage (Pianta et al. 2018).

Heavy metals in neurotoxicity

Neurotoxicity refers to the harmful effects of various substances or agents on the nervous system, including the brain, spinal cord, and peripheral nerves. These substances, known as neurotoxins, can interfere with the normal functioning of nerve cells and, in some cases, cause damage to neural tissues. Neurotoxicity can lead to a wide range of neurological symptoms and conditions, which can vary in severity depending on the type and dose of the neurotoxin, as well as the duration of exposure.

Mercury (Hg) Reliable indications of neurodevelopmental repercussions, encompassing heightened activity levels, compromised motor coordination, impaired memory, and reduced sociability. In mature subjects, observed neurobehavioral outcomes encompass heightened activity, impaired coordination, and compromised learning and memory (Costa et al. 2021). Adult subjects have also displayed evident neurotoxic manifestations like hindlimb crossing, ataxia, tremors, partial paralysis, alongside neuropathological alterations in sensory motor zones within the central nervous system, specifically the dorsal spinal tract and cerebellum.

Cadmium (Cd) In a study conducted, a group of 31 men employed in a refrigerator coil manufacturing facility and exposed to cadmium occupationally (with an average exposure duration of 14.5 years) demonstrated a moderate correlation between cadmium exposure and diminished performance in neuropsychological evaluations gauging attention, psychomotor speed, and memory (Tang et al. 2019). In a separate investigation, it has been explored the presence and severity of olfactory dysfunction among individuals subjected to prolonged exposure to cadmium fumes during brazing operations. A significant impairment in olfactory function was observed among the exposed workers in comparison to the reference group ($p < 0.003$) (Chevignard et al. 2020). *Chromium (Cr).* In a chrome plating facility marked by inadequate exhaust systems leading to exceptionally high concentrations of chromium trioxide fumes, employees experienced symptoms such as headaches, weakness, and dizziness when working above the chromate tanks (Sankhla and Kumar 2019). Given the advancements in industrial hygiene over time, it is unlikely that substandard working conditions of a similar nature persist in the USA. Findings from olfactory perception assessments conducted on workers engaged in chromium plating activities in An-San, Korea, with an average employment duration of 7.9 years indicate that individuals with past exposure history displayed notably higher olfactory recognition thresholds when compared to control subjects (Kitamura et al. 2003). Airborne levels of chromium (VI) spanned from 0.005 to 0.03 mg m^{-3}, while concentrations of chromium (III) ranged from 0.005

to 0.06 mg m^{-3}. While the exact origin of this alteration was not ascertained, the researchers propose that chromium could potentially exert a direct influence on the olfactory nerve (Hasan and Muhammad 2020).

Copper (Cu) Three investigations examining the neurological consequences of copper inhalation in humans were identified. Factory workers exposed for a duration of 3 years reported experiencing symptoms such as headache, vertigo, and drowsiness. The exposure commenced at a peak concentration of 464 mg m^{-3} and gradually decreased over the course of 3 years to reach 111 mg m^{-3} of copper dust (Sankhla and Kumar 2019). Inadvertent inhalation of copper dust, along with contact on the facial skin, led to sensory impairment in a 2-year-old girl (Donoso et al. 2007). An epidemiological investigation focused on children aged 8 to 12 years revealed a noteworthy correlation between airborne copper exposure and compromised motor performance, alongside observable indications of cerebral impairment (Pujol Martí et al. 2016). Copper concentrations, primarily linked to vehicular emissions, were quantified both within and outside school premises. A total of 2827 children underwent behavioral assessments, while a subset of 263 children underwent brain imaging. Notably, children with elevated exposure exhibited diminished reaction times, while imaging demonstrated an association between copper and heightened gray matter concentration in the striatum. Additionally, copper appeared to correlate with modifications in the diffusion architecture of neural tissue (Pujol Martí et al. 2016). Neurological repercussions ensuing from the ingestion of copper compounds such as copper sulfate, copper oxychloride, and copper-8-hydroxyquinolate were also documented in various other instances. Among the prevailing effects, headaches, dizziness, agitation, and drowsiness were the most frequently reported (Du and Mou 2019; Gunay et al. 2006; Malik and Mansur 2011). *Lead (Pb).* Reduced cognitive capabilities encompassing attention, memory, and learning, alongside modifications in neuromotor and neurosensory capacities, shifted mood and behavioral patterns potentially implicated in compromised learning abilities, peripheral neuropathy, and encephalopathy. This manifests as diminished cognitive function, including attention, memory, and learning, coupled with changes in neuromotor and neurosensory capacities. Mood and behavior alterations are also evident, along with decreased peripheral nerve conduction velocity (Sweeney et al. 2019).

Heavy metals and cardioprotective effects

Cardiotoxicity refers to the toxic or harmful effects of various substances or agents on the heart muscle (myocardium) and the cardiovascular system as a whole. These substances, known as cardiotoxins, can interfere with the normal functioning of the heart, potentially leading to heart-related problems and conditions. Cardiotoxicity can range from mild, reversible effects to severe, life-threatening cardiac damage.

Mercury (Hg) The presence of corroborative data indicating elevated blood pressure, modified cardiac performance, favorable effects on myocardial contraction strength, and adjustments in baroreceptor reflex sensitivity (Teles et al. 2022). *Cadmium (Cd)*. An inquiry into the well-being of laborers at a manufacturing facility engaged in the production of cadmium-containing electrodes used for battery manufacturing. Fifty-eight workers, ranging from 30 to 50 years of age, were divided into two cohorts according to their duration of employment at the facility. Comprehensive clinical examinations were conducted to evaluate self-reported symptoms alongside corresponding morphological and functional alterations in the respiratory, cardiovascular, and excretory systems (Yang et al. 2020). The cardiovascular assessment predominantly produced inconspicuous findings. *Chromium (Cr).* There exists limited information concerning the cardiovascular repercussions in humans following inhalation exposure to chromium and its compounds. A study was conducted in an Italian chromate production facility, where exposure of chromium (VI) levels equaled or exceeded ≥ 0.01 mg m^{-3}. Within this survey, 22 out of 65 workers engaged in the manufacturing of dichromate and chromium trioxide for a minimum of 1 year underwent electrocardiogram assessments. Notably, no abnormalities were detected in these assessments (Hossini et al. 2022). A comprehensive assessment aimed at determining the health status of workers involved in chromate production across seven US plants concluded that no discernible connection existed between exposure to chromates and the occurrence of heart disease or alterations in blood pressure. The facilities included diverse manufacturing processes that led to worker exposure to chromite ore (with an average time-weighted concentration ranging from 0 to 0.89 mg m^{-3}); water-soluble chromium (VI) compounds (ranging from 0.005 to 0.17 mg m^{-3}); and acid-soluble/water-insoluble chromium compounds, including basic chromium sulfate, potentially involving trivalent chromium (ranging from 0 to 0.47 mg m^{-3}) (Kierczak et al. 2021).

Copper (Cu) No toxicity investigations concerning human fatalities resulting from inhalation exposure to copper were identified. Nevertheless, copper present in PM 2.5 particulate matter has been linked to an elevated likelihood of mortality due to cardiovascular disease (Badaloni et al. 2017; Lavigne et al. 2019; Wang et al. 2020; Valdés et al. 2012) and ischemic heart disease mortality (Badaloni et al. 2017; Lavigne et al. 2019), and cerebrovascular disease mortality (Valdés et al. 2012). Ostro et al. (2008, 2015) specifically highlighted an elevated susceptibility to cardiovascular disease mortality within the Hispanic population. Additionally, a cohort study involving teachers in California demonstrated an increased risk of mortality from ischemic heart disease (Ostro et al. 2015). However, the precise causal factor behind these effects remains uncertain. It is not definitively established whether the observed impacts stem from copper itself or are linked to PM2.5, which is inherently associated with unfavorable cardiovascular health outcomes, including cardiovascular mortality (EPA 2019). Elevated serum copper levels were linked to an escalated susceptibility to death from coronary heart disease in adult NHANES participants (Ford 2000). *Lead (Pb).* Elevated systolic and diastolic blood pressure, heightened susceptibility to hypertension, atherogenesis, modified cardiac conduction, escalated vulnerability to cardiovascular ailments, and heightened mortality attributed to cardiovascular disease (Ren et al. 2021).

Impact of pharmaceuticals

Nonsteroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen, naproxen, and diclofenac are widely utilized to alleviate pain and inflammation. Prolonged or high-dosage consumption of these medications can result in reduced renal blood flow, potentially contributing to acute kidney injury and worsening pre-existing chronic kidney disease. The impact of NSAIDs on the kidneys encompasses both immune-mediated and non-immune-mediated mechanisms of damage (Perazella 2012). Immune-mediated injury arises from immunologic responses targeting either exogenous antigens or intrinsic nephritogenic antigens that are processed by tubular cells, whereas cell-mediated immunity plays a contributory pathogenic role. Naproxen, a non-selective cyclooxygenase inhibitor, is recognized for inducing renal failure through mechanisms involving renal papillary necrosis, tubular impairment, and interstitial nephritis (Cabassi et al. 2020). Aminoglycosides such as gentamicin and amikacin, potent antibiotics employed against severe bacterial infections, carry a risk of nephrotoxicity, particularly when employed at elevated dosages or extended durations. Their usage can result in renal tubular impairment, potentially leading to acute kidney injury (Aronoff et al. 2007). Acyclovir, an antiviral agent targeting herpes infections, has the potential to induce crystalline nephropathy, characterized by the formation of acyclovir crystals within renal tubules, with potential consequences for kidney integrity (Morfín and Gupta 2018).

Cephalosporins like cefixime, cefuroxime, and cefazolin have been linked to a form of encephalopathy that exhibits characteristics of temporo-spatial disorientation and EEG findings of triphasic waves (Chow et al. 2003; Bragatti et al. 2005). Individuals with impaired renal function are believed to face an elevated susceptibility to this encephalopathy (Chatellier et al. 2002; De silva et al. 2007). The presence of nonconvulsive status epilepticus (NCSE) has been extensively recorded in association with the fourth-generation cephalosporin and cefepime. Due to the frequently covert nature of these seizures, the only evident clinical indication might be a non-localizing encephalopathy, with a definitive diagnosis requiring EEG examination. The treatment of NCSE often entails the temporary use of anticonvulsants like benzodiazepines, phenytoin, and valproic acid for patient management (Capparelli et al. 2005). Cefepime has additionally been associated with a heightened likelihood of unexplained mortality in neutropenic patients during hospitalization, particularly in contrast to treatment with alternative antibiotics (Herishanu et al. 1998; Lam and Gomolin 2006). Consequently, healthcare practitioners should exercise vigilant monitoring when employing cefepime in patients with neutropenia or compromised renal function. Within the category of nonsteroidal anti-inflammatory drugs (NSAIDs), which encompasses aspirin, ibuprofen, and NS-398, the engagement of the mitogen-activated protein kinase (MAPK) p38 has been established (Rossi Paccani et al. 2003). This MAPK p38 holds a significant role in overseeing the microglial production of pro-inflammatory compounds like TNF-α and NO (Koistinaho and Koistinaho 2002). The initiation of p38, a pivotal molecular mediator, instigates the phosphorylation of various downstream kinases and transcription factors. It regulates the mRNA stability of proinflammatory cytokines such as TNF-α and impacts the accessibility of chromatin for transcription factors like NF-κB. Consequently, modifications in p38 activation due to NSAIDs could potentially induce a substantial reconfiguration of the signaling network linked to this kinase in microglia. Significantly, a protective effect of rofecoxib has been observed, potentially achieved by inhibiting the phosphorylation of p38MAPK, as evidenced in an in vivo model of excitotoxic degeneration (Scali et al. 2003).

NSAIDs, across the spectrum, possess the capacity to diminish renal function by obstructing COX-1 and/or COX-2 enzymes expressed in the kidneys (Weir 2002). The surge in cardiovascular risk among NSAID users has been postulated to be linked to heightened blood pressure arising from COX-2 inhibition within the kidneys-a phenomenon that is notably absent with over-the-counter (OTC) dosages (Moore et al. 2014). Among all NSAIDs, there exists a range of influences on vasodilation and sodium excretion, brought about by the modulation of prostanoid production (such as PGE2). This effect can lead to hypertension, a recognized risk factor for cerebrovascular and thromboembolic events (Bowman et al. 2006; Malmberg and Yaksh 1992). The COX isozymes are ubiquitously present in diverse body tissues and exert varying influences on hemostasis via prostanoids (Timmers et al. 2007; Francois et al. 2005). Platelets play a pivotal role in cardiovascular hemostasis and solely express COX-1, distinct from endothelial cells that express both COX-1 and COX-2. The synthesis of TXA2, facilitated by COX-1, precipitates platelet aggregation, vasoconstriction, and a rise in vascular and cardiac remodeling. The cardiovascular risks attributed to NSAID usage stem from heightened blood pressure arising due to COX-2 inhibition within the kidneys and modifications in sodium and fluid retention (Patrignani et al. 2014). The presumed elevation in blood pressure observed during extended NSAID usage is postulated to augment the likelihood of cardiovascular risk, considering that hypertension is a recognized factor contributing to cardiovascular disease. This escalated risk is essentially tied to prolonged exposure. Additionally, NSAIDs have been implicated in exacerbating heart failure and inducing fluid retention through their influence on renal function and modulation of fluid balance (Aw et al. 2005). The suppression of COX-2 by NSAIDs leads to a reduction in PGI2 and PGE2 levels within the renal cortex and juxtaglomerular cells, culminating in diminished renal blood flow and glomerular filtration rate (Tegeder and Geisslinger 2006). Furthermore, certain indications suggest that NSAIDs might impede aldosterone metabolism, carrying potential consequences for fluid retention, blood pressure, and the remodeling of cardiovascular structures (Knights et al. 2009). Notably, fluid retention is linked to the deterioration of heart failure in susceptible individuals, particularly among the elderly (Gislason et al. 2009).

Impact of pesticides and fertilizers

Although pesticides are intended to control unwanted pests, their use has raised concerns about potential risks to human health. Pesticide exposure occurs through direct contact in occupational, agricultural, and household settings, and it can also be transmitted indirectly through dietary intake (Kim et al. 2017). Exposure to pesticides has been associated with a range of health conditions, including cancer, disturbances in hormonal balance, asthma, allergic reactions, and heightened sensitivity (Van Maele-Fabry et al. 2011). Evidence also suggests that pesticide exposure can have adverse effects, including birth defects, diminished birth weight, and fetal mortality (Baldi et al. 2011; Wickerham et al. 2012). Individuals with proximity to pesticide exposure have shown an elevated risk of various cancers, such as neuroblastoma, leukemia, soft tissue sarcoma, Burkitt lymphoma, non-Hodgkin lymphoma, Wilm's tumor, lung cancer, ovarian cancer, and rectal cancer (Alengebawy et al. 2021). Multiple epidemiological and clinical studies have established an association between pesticide toxicity and the manifestation of symptoms such as asthma and bronchial hyper-reactivity. Pesticide contact can exacerbate asthma by causing inflammation, irritation, or weakening the immune system (Amaral 2014; Hernández et al. 2011). Studies have explored the role of pesticides, along with other environmental factors, in the onset of Parkinson's disease (PD). Many studies have sought to establish a link between pesticide exposure and PD, and the results consistently indicate a significant positive correlation. Notably, paraquat has been identified as having a positive association with an increased risk of PD. Studies by Freire and Koifman (2012) and Brouwer et al. (2017) have highlighted connections between PD and specific pesticide types, including herbicides (like paraquat), insecticides (such as organophosphates and rotenone), and fungicides (like cyprodinil, fenhexamid, and thiophanate-methyl). Moreover, exposure to such pesticides at sufficient concentrations has been shown to result in abnormalities in sperm, impaired fetal growth, reduced fertility, an increased risk of abortions, and the potential for birth defects (Alengebawy et al. 2021).

Exposure to pesticides has been linked to various cardiovascular complications, including irregularities in electrocardiograms, heart attacks (myocardial infarction), compromised function in both systolic and diastolic phases of the cardiac cycle, functional changes in the structure of the heart (remodeling), histopathological damage such as bleeding, vacuolization, signs of cell death (apoptosis), and tissue degeneration. These complications are accompanied by biochemical disruptions, including disturbances in lipid profiles and elevated oxidative stress in both systemic circulation and cardiac tissues. This exposure can also result in genetic alterations in cardiac cells, potentially leading to impaired function (Nikolaos et al. 2022). Certain pesticides could influence the neuroendocrine system in humans by either activating or inhibiting estrogen receptor (ER) binding. For instance, pesticides like DDE, vinclozolin, fenitrothion, and procymidone act as blockers for the androgen receptor, while others like DDT and methoxychlor act as stimulants for the ER. Organochlorine pesticides can disrupt the endocrine system in multiple ways, including their effects on various receptors (Hernández et al. 2013).

The global use of inorganic nitrogen fertilizers on various crops has been consistently increasing over the past decades. While nitrogen fertilizers contribute significantly to higher yields, their excessive application has raised significant concerns for human health. The rate of nitrogen fertilizer use is closely linked to the accumulation of nitrates in the environment, groundwater, and leafy/root vegetables (Ahmed et al. 2017). The main sources of human exposure to nitrogen fertilizers are contaminated drinking water containing nitrates and the consumption of excessive amounts of root and leafy vegetables (Jones et al. 2016). These exposures have been associated with various adverse health effects, such as thyroid cancer, hypertension, testicular cancer, stomach cancer, neural tube defects (NTDs), increased infant mortality, birth defects of the central nervous system, diabetes, miscarriages, respiratory tract infections, and alterations in the immune system (Ahmed et al. 2017; Hakeem et al. 2017).

Impact of industrial dyes

Dyes used in various industries such as textile, leather, and paper industries can pose potential health risks to humans (Gürses et al. 2016; Al-Tohamy et al. 2022). Workers handling reactive dyes face the possibility of developing allergic reactions like contact dermatitis, allergic conjunctivitis, rhinitis, and occupational asthma (Al-Tohamy et al. 2022). Some dyes, especially azo dyes, have the potential to cause mutations, and specific azo dyes and their derivatives are associated with human bladder cancer (Josephy and Allen-Vercoe 2023). One example is Sudan I, an azo-lipophilic dye used in textiles and food, which can be enzymatically transformed into cancer-causing aromatic amines by intestinal microorganisms. Disperse Red 1 dye has been found to be mutagenic in human hepatoma cells and lymphocytes due to its ability to increase micronuclei frequency, indicating chromosome-level mutagenicity (Antoine 2016). Furthermore, Disperse Orange 1 dye induces DNA damage by causing base-pair replacements and frameshift mutations, ultimately altering reading frames (Chequer et al. 2009). Direct Blue 14 dye has shown the potential to generate carcinogenic amines when exposed to bacteria on human skin. Similarly, Disperse Yellow 7 dye, when degraded in natural waterways, produces amines known for their carcinogenic properties (Balakrishnan et al. 2016).

Azure B, the major metabolite of Methylene Blue, is a cationic dye that can insert itself into the helical structure of DNA and duplex RNA (Haq and Raj 2018). This dye might also associate with the lipid membrane of animal cells, potentially acting as a significant and reversible inhibitor of monoamine oxidase A (an intracellular enzyme crucial in human behavior) (Li et al. 2013). The inhibitory effects of Azure B on enzymes like glutathione reductase, which plays a role in cellular redox balance, have also been explored (Couto et al. 2016). On a different note, triphenylmethane dyes like Basic Red 9, commonly used in industries like textiles, leather, paper, and ink, are classified as carcinogenic to humans. This is due to the production of aromatic amines during the anaerobic degradation of these dyes, leading to issues like allergic dermatitis, skin irritation, mutations, and cancer (Sivarajasekar and Baskar 2015). Crystal Violet, another type of triarylmethane dye, can induce mitotic poisoning, resulting in chromosomal damage and abnormal metaphase accumulation (Mani and Bharagava 2016). This highly carcinogenic compound has been associated with reticular cell sarcoma in various organs, including the vagina and bladder (Lellis et al. 2019). Additionally, Crystal Violet has the potential to cause chemical cystitis, as well as irritation of the skin, digestive system, and respiratory tract, possibly leading to renal failure (Mani and Bharagava 2016). Azo dyes and their degradation products are often linked to the development of malignancies of spleen and urinary bladder in humans and animals, besides causing other serious health risks like hemorrhage, nausea, and skin ulceration (Ceretta et al. 2020; Kumar et al. 2020). According to studies, persistent organic pollutants (POPs) released in TIWW contain significant proportion of additives, detergents, pesticides, mordants, surfactants along with others including finishing chemicals (Garg et al. 2020). Malachite green (MG) is a PCP that adversely affects humans by reducing food intake, stunting growth and fertility, and damaging the kidney, spleen, heart, and liver (Chowdhary et al. 2020a, b). Additionally, it results in an increase in the number of white blood cells (WBCs), reduces the number of red blood cells (dyscrasia), causes anemia and lesions on the eyes, skin, limbs, and bones (Sartape et al. 2017). The US Food and Drug Administration forbade the use of MG dye because of its hazardous effects, but it is still utilized in a number of nations. A form of azo dye called tartrazine is used in the food, pharmaceutical, textile, and cosmetic sectors. It has been linked to a number of health issues, including eczema, allergies, asthma, and hypersensitivity as well as having carcinogenic and mutagenic effects on living things (Kumar et al. 2020).

Methods of detection for different pollutants

The detection of pollutants (both inorganic and organic) in the water bodies released as effluent from industries, and through use of agrochemicals, pharmaceutical products, and others, over the time has brought increasing concern for their adverse effects on environment and on the human health (Kosjek et al. 2013; Heath et al. 2016; Golubovic et al. 2019). As their release in the environment is often correlated as a strong risk factor for the occurrence of different diseases and on the overall morbidity and mortality, it becomes imperative to have a strong monitoring system that could evaluate the actual concentration and interpret effect on the environment and on human health (Table 4). Keeping this in view, a wide range of analytical approaches such as GC–MS, LC-IT-TOF–MS, and MALDI-TOF–MS have been developed and intensively implemented in quantifying the detectable limit of pollutants and investigate the presence of different pollutants and as such associated health concerns (Comerton et al. 2009; Kosjek et al. 2013; Kunancheva and Stuckey 2014; Skufa et al. 2021). Several studies have performed on the extraction and detection of pollutants in the aquatic environment. Renew and Huang (2004) performed a check for antibiotics in wastewater by using anion exchange

Table 4 Table summarizing different aspects of pollutants

Compound	Class of drug/PCPs	Source	Extraction method	Recovery %	Analytical instrument	R^2	LOD (ng L^{-1})	LOQ (ng L^{-1}	RSD%	Reference
Ibuprofen	NSAID	River water	Solid phase extraction (SPE)	22	LC–MS; ESI(NI)-MS	0.9998	21	0.98	5	Shah et al. (2020)
Salicyclic acid	Keratolytic	Treated water	SPE; SPE HLB	34	LC–MS; ESI(NI)-MS	0.9922	2	0.29	7	Xu et al. (2009), Sharma et al. (2020)
Diclofenac	NSAID	Raw wastewater	SPE	84	LC–MS/MS	0.9998	1.1	2.93	7	Alquadeib (2019), Digambar et al. (2015)
Triclosan	Antibacterial	Tap water	SPE	82	LC–MS/MS	0.9997	6	2.7	40	Montaseri and Forbes (2016)
Ketoprofen	NSAID	Ground water	SPE	83		0.9945		0.5	2	Yadav et al. (2016)
Atenolol	Beta blocker	Wastewater	Gel- electromembrane extraction	99.21	LC–MS/MS	0.9983	1.5	5	0.6	Syed and Mohammed (2014)
Linezolid	Antibiotic	Sewage storage	SPE	84	LC–MS/MS	0.9978	3	0.12	0.78	Fernandes et al. (2020), Galitzine et al. (2018)
Ampicillin	Antibiotic	Sewer water	SPE	85	LC–MS/MS	0.9947	2	0.066	7.7	Tótoli and Salgado (2014)
Verapamil	Calcium channel blocker	River water	SPE	87		0.9975	1.2	0.073	5	McAllister and Howell (1976), Wood (2015)
Acetaminophen	Analgesic	Ground water	SPE	97.15	LC–ESI–MS	0.9965	3	0.14	1.04	Ebrahimi et al. (2021)
Carbamazepine	Antileptic	River water	SPE	98	UHPLC-ESI–MS/MS	0.9999	0.10	0.7	68	Datar (2015)
Fluconazole	Antifungal	Sewer water	LLE (Liquid Liquid extraction)	97	LC–MS/MS	0.9955	0.10	0.01	0.64	Alffenaar et al. (2010), Göğer and Aboul-Enein (2001)
Voriconazole	Antifungal	Sewer water	LLE	99	LC–MS/MS	0.9980		0.2	0.53	Alffenaar et al. (2010)
Naproxen	NSAID	River water	SPE	98	LC–ESI–MS/MS	0.9910	0.9	0.1	0.6	Yilmaz et al. (2014)
Trimethoprim	Antibiotic	River water	PLE (Pressurised liquid extraction)	82	HPLC	0.9700	15	0.59	3.53	Sayar et al. (2010)
Moxifloxacin	Antibiotic, fluoroquinole	Sewer water	SPE	86	LC–MS/MS	0.9999	1.6	0.53	0.17	Laban-Djurdjević et al. (2006)
Cetirizine	Antihistamine	River effluent	LLE	99.19	HPLC	0.9990	1.75	0.50	0.94	Arayne et al. (2005)
Glibenclamide	Hypoglycemic drug	River water	DMSPE	97	RP-HPLC	0.9971	0.032	0.62	1.5	Haq et al. (2014),

Table 4 (continued)

Compound	Class of drug/PCPs	Source	Extraction method	Recovery %	Analytical instrument	R^2	LOD (ng L^{-1})	LOQ (ng L^{-1}	RSD%	Reference
Citalopram	Selectiveserotonin-reuptakeinhibitor	River effluent	LLE	96.2	HPLC	0.9440	0.15	10	0.7	Sarıkaya et al. (2021)
Terbinafine	Antimycotic	Sewer water	SPE	98.54	HPLC	0.9990	0.30	0.42	0.55	Kanakapura and Penmatsa (2016)
Sulfanilamide	Antibiotic	Ground water		87		0.9730	0.1	0.1	3.8	Ni et al. (2009)
Cyclophosphamide	Antineoplastic	River water	LLE; SPE		UPLC-MS/MS	0.9771	0.3	5	0.8	Sottani et al. (2008)
Venlafaxine	Antidepressant	River wate	SPE	93	LC–MS-MS	0.9880	3	1.72	0.79	Somasekhar et al. (2009), Dziurkowska and Wesołowski (2013)
Tri-isobutylphosphate	Flame retardant	Tap water	SPE	82	LC–MS/MS; LC–ESI–MS/MS	0.9996	14		4.6	Rodil et al. (2009)
Triethyl phosphate	Flame retardant	Wastewater; surface and drinking water	SPE; Liuqid liquid extraction	92	LC–MS/MS; PTV-GC-EI-MS	0.9998	2	0.2	8.5	Wang et al. (2014)
Diethyl hexyl phosphate	Flame retardant	Raw water	SPE	58	LC–MS/MS	0.9935	3		6	Takeuchi et al. (2014)
DEET	Mosquito repellent	Treated water	SPE	70	LC–MS/MS	0.9912	0.6	1	4	Dos Santos et al. (2019), Vilar et al. (2018)
Benzotriazole	UV stabilizer	River water	SPE	87	GC–MS	0.9941	0.0018	0.1	13	Kotowska et al. (2021)
UV-329	BUVSs	Ground water	PLE	71	GC–MS/MS				0.21	Liu et al. (2014)
Iohexol	X-ray contrast media	Waste water		95	HPLC	0.9934		0.25	6.39	Soman et al. (2005)
Mecoprop	Herbicide	Raw waste water	SPE	74	LC–MS/MS	0.9972	2.5	0.0002	2.4	Heberer and Stan (1996)
Endosulfan	Pesticide	Surface water	Liquid and solid phase extraction	80		0.9980	0.04	0.2	6	Nishadini et al. (2014), Saadati et al. (2013), Hussen et al. (2006)
Endrin	Pesticide	Surface water	PLE	65	GC–MS	0.9946	0.11	0.1		Castillo et al. (2011), Pastor Belda et al. (2021)
Chlorpyrifos	Pesticide	Surface water	SPE	80	LLE-GC–MS	0.9770	0.04	0.36	1	Schwantes et al. (2020), Phung et al. (2012)

Table 4 (continued)

Compound	Class of drug/PCPs	Source	Extraction method	Recovery %	Analytical instrument	R^2	LOD (ng L^{-1})	LOQ (ng L^{-1})	RSD%	Reference
Phenoxyacetic acid	Pesticide	Ground water	LLE	99.9	UHPLC	0.9980	0.12	0.023	1.8	McManus et al. (2014), Pei et al. (2019), Tsyganok and Otsuka (1999)
Diuron	Pesticide	River water	LLE	96	HPLC	0.9997	0.43	0.5	3.5	Felicio et al. (2016), Wong et al. (2015)
Atrazine	Pesticide	Surface water	SPE	100	GC-EI-MS/MS	0.9660	0.05	20	0.7	Blanchoud et al. (2020), Della-Flora et al. (2018), Müller et al. (2003)
Heptachlor	Pesticide	River water	SPME	95	GC–MS	0.9901	0.25	0.01	3.8	McManus et al. (2013), Yera and Vasconcellos (2021), Chusaksri et al. (2006)

cartridge that removes chances of interference of organic matter followed by detection with LC–ESI–MS. Similarly, Zuehlke et al. (2005) performed check for oestrogens by adopting solid phase extraction (SPE) followed by LC–MS/MS) with electron spray ionization (ESI). A similar check for at least 10 different pharmaceutical compounds in wastewater was performed by performing SPE followed by gas chromatography tandem mass spectrometry (GC–MS/MS) (Gómez et al. 2007). In another study, Baugros et al. (2008) performed analysis for 33 different compounds among aquatic water bodies using SPE followed by the use of GC–MS and LC–MS/MS. Gros et al. (2009) performed analysis of almost 73 different pharmaceutical products by extraction through SPE followed by analysis using LC–MS/MS with hybrid ion-trap mass spectrometer. Despite this, majority of the analytical methods developed focuses on the detection of only special classes of compounds and is not featured for analysis of multi-class compounds.

Remediation methods for water pollutants

Taking toxicity of different pollutants into consideration, a large number of strategies based on physical, chemical, and biological approaches have been formulated to reduce or eliminate contaminants from wastewater to safeguard water for human consumption (Fig. 3).

Chemical precipitation

In chemical precipitation, treatment of contaminants, like heavy metals and dyes with chemical precipitants like sulfides, lime, and iron, results in their precipitation and as such removal from different substrates (Verma and Balomajumder 2020). In the chemical precipitation procedure, one can optimize the removal capacity and efficiency by regulating the parameters of initial concentration, pH (basic, in the range of 9–11), charge, and temperature (Gunatilake 2015). In the hydroxide precipitation procedure, coagulants enhance the removal of heavy metals by filtering or sedimentation. The most popular chemical precipitation approach for color removal is hydrogen peroxide (Bouyakoub et al. 2011). Zhang et al. (2011) achieved removed of prominent dyes such as acid orange II, reactive light-yellow K-6G, and others using this method. In the study, 4 g^{-1} sorbent effectively removed 94.6% of the color from industrial effluents. The system's quick kinetics was confirmed by the dye's removal in less than 90 s. It was also established that the filtered water was non-toxic. This research demonstrated the feasibility of large-scale water purification for drinking and other purposes using chemical precipitation. Oladoja et al. (2011) studied in situ hybridization of Methylene blue and Congo Red with calcium derivative particles generated from gastropod shells.

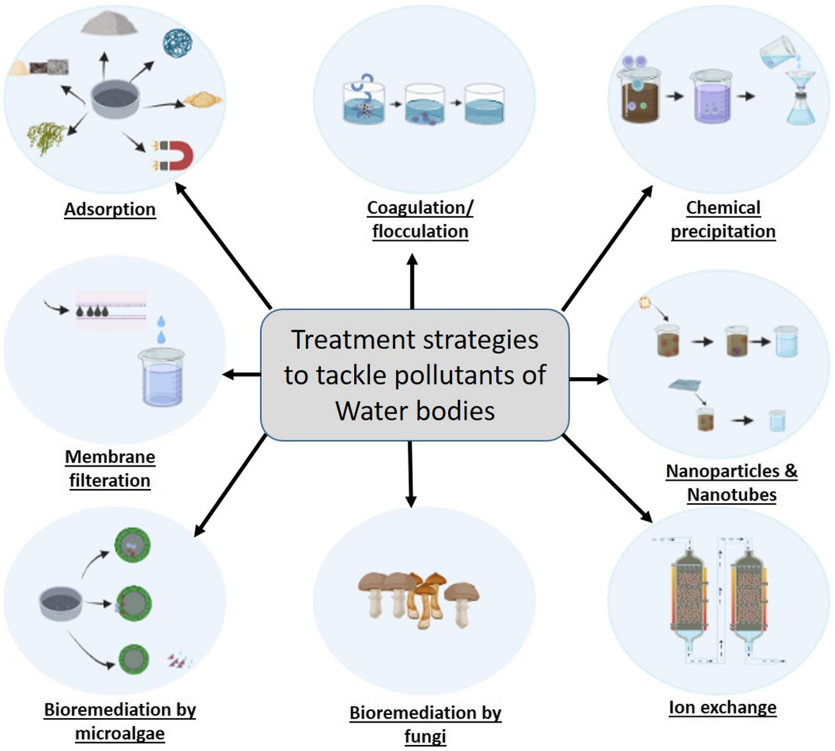

Fig. 3 Contaminants of different origins and their possible abatement using different strategical approaches

They observed the method capable of removing about 67% and 77% of Methylene blue and Congo Red following the chemical precipitation method. Though the method was found to have no dependency on the initial concentration used, nor on the presence of ions and their strength during the dye removal procedure, increase in ionic strength was found to enhance accelerated sludge settling rate. Compared to this, gravity settling or filtration is used to remove the sludge that results from precipitation by metal sulfide. Toxicity associated with H_2S and sulfide ions necessitates the adoption of pre- and post-treatment strategies and a careful check of reagent addition. Though chemical precipitation serves the purpose of being efficient in removing organic dyesand heavy metals from wastewater, the accompanying sludge, and high chemical costs make it unsuitable for industrial use.

Coagulation/flocculation

Coagulation-flocculation is regarded as an efficient physicochemical technique in the removal of heavy metals following agglomeration of small particles and colloids into bigger particles (Xu et al. 2019). The first step in the coagulation-flocculation process involves addition of a coagulant such as ferric sulfate and its polymeric form, aluminum sulfate, polyacrylamide and others to water for promoting coalescence of suspended colloidal particles into aggregates referred to as flocs (Teh et al. 2016; Xu et al. 2019). In the second step, flocs on gently agitation settle and are finally discarded as sludge. Due to its wider adaptability, the method is primarily adopted for use in the pre-, post-, or primary wastewater treatment (Teh et al. 2016). While accessing the parameters for employment in the removal of Cibacron Red FNR using an inorganic organic composite polymer in flocculation technique, five parameters including composite polymer dose, pH, dye concentration, agitation speed, and agitation time were regarded as the most important variables in the dye removal process (Lee et al. 2014). The study motivated and encouraged a number of other researchers to create safer and more efficient coagulation-flocculation systems for wastewater treatment. In addition to polymeric coagulants, a number of naturally occurring compounds obtained from a variety of plants such as *Vicia faba*, *Moringa oleifera*, and *Moringa stenopetala* have also been employed as coagulants in the coagulation-flocculation process (Chonde and Raut 2017). One of the most extensively researched natural coagulants is *Moringa oleifera* attributed to its water-soluble cationic coagulant protein that possess ability to lower turbidity, COD, and TDS of the wastewater being treated (Feihrmann et al. 2017). *M. oleifera* seeds are also utilized as a primary coagulant in wastewater treatment owing to their excellent efficacy in removing turbidity from river waters and for not altering pH and alkalinity of the treated (Díaz et al. 2018).

Ion exchange

The ion exchange process employs its basic property in facilitating exchange of ions between a solid and a liquid phase. In this process, an insoluble material facilitates exchange of chemically identical entities having similar charge between itself and the ions present as part of the electrolytic solution (Kurniawan et al. 2006). The insoluble material referred to as resin facilitates exchange of ions both anionic (anion exchangers) and cationic (cation exchangers) solutes with different charges in the three-dimensional matrix (Dula and Duke 2019). Considered as an efficient and affordable solution to the removal of contaminants, it is more often used in the removal of dyes from aqueous solution via formation of the stable bond between functional groups present on the ionic resins and the charged dyes (Al-Enezi et al. 2004). The structure of resin with sulfonic acid as functional group serves best for use in the ion exchange-based removal of dyes (Zamora-Ledezma et al. 2021). While studying the removal of acid dyes (Acid Orange-7 and -10) from water, Greluk and Hubicki (2013) checked the effectiveness of two very basic and one weakly basic anion exchangers and observed that basicity of the resins has a significant effect on dye adsorption capacity, and dye molecules with more sulfonic groups have an increased ability to form bonds with all varieties of anion exchangers. While studying the effectiveness of cation exchange resins for eliminating Basic Blue 3, Wawrzkiewicz (2013) reported that 99.9% of the dye can be eliminated within just 1 h of contact time. A high quantity of SDS, however, reduced the efficacy of removal because of interactions between the dye and the surfactant. To eliminate the colors Orange G and Red RWO, NDMP, a quarternized magnetic resin that works exceptionally well in the pH range of 2–11 was developed (Shuang et al. 2012). In this process, the resin was reused again and again for almost 20 times with only a slight decrease in its adsorption efficiency. Additionally, some naturally occurring substance-based ion exchangers have also been employed to remove Azocarmine B (Constantin et al. 2013). With biodegradable nature, pullulan microsphere-based ion exchanger (considered as a low-cost ion exchanger) was found to have an adsorption capacity of 113.63 mg g^{-1} for application in the removal of dyes. Reactive Red 239 and Reactive Blue 250 have been removed from natural zeolite following elution with the appropriate reagents (Alver and Metin 2012).

Adsorption

Adsorption is the process of condensation of molecules or ions (adsorbate) on the surface of the adsorbent. Adsorption is considered as one of the finest ways in the removal of contaminants such as heavy metals and dyes with low energy requirement, high removal capacity, and no special technical requirement for its operation (Burakov et al. 2018). The process is categorized into physisorption or chemisorption based on how well adsorbate undergoes adsorption on the surface of adsorbent (Gupta et al. 2009). A series of forces of attraction including hydrophobic, hydrogen, and van der waals are employed in binding dye molecules to the surface of an adsorbent (Kyzas, et al. 2012). Porous characteristics are used in adsorbents to increase the overall surface area and enable fluid to flow through more rapidly. Being an easy and affordable way of removing pollutants from water and wastewater, removal of contaminants such as heavy metals and dyes is achieved through the application of a variety of adsorbents such as activated carbon, polymer-based materials of different compositions, magnetic materials, besides having the usage of agricultural and industrial wastes.

Activated carbon Activated carbons are well known for their extended surface area (~ 3000 m^2 g^{-1}) with an excellent adsorbing capacity to hold a series of contaminants (Dias et al. 2007). The genesis of activated carbons from natural resources with strong sorption qualities, such as biomass, may be linked to their great adsorption abilities and economic potential. Relying on the properties of surface area and pH of the solution, activated carbons develop an electric charge attributed to either breakdown of the carbon's functional group or the adsorption of ions generated in an aqueous solution (Dias et al. 2007). The prominent functional groups responsible for adsorption of ions on the surface of activated carbon are hydroxyl ($^-$OH), carboxylic ($^-$COO), or an epoxy group. Several physical (use of steam, high temperature, CO_2 along with inert gases to eliminate the interference of non-carbonaceous components) and chemical (use of organic and inorganic moieties to amend the adsorption capacity) approaches have been utilized to generate and modify activated carbons in order to boost their adsorption capacity (Dias et al. 2007). Of them, chemical treatment-based activation of activated carbon is done at a relatively low temperature to facilitate its reaction with the carbon skeleton. On comparing chemically activated carbons to physically activated carbons, it was found that chemically activated carbons had a higher adsorption capacity. Activated carbon is generally considered as the most popular strategy for employment in the adsorption of metal contaminants. Activated carbon having agroindustrial background has shown the adsorption capacity of ~ 900 mg g^{-1} in the procedural strategy employed in the removal of Cr^{3+} from water (Yunus et al. 2020). In order to lower the cost of activated carbon treatments, a series of raw materials ranging from agricultural residues to petroleum-based products have been employed in creating an environmentally friendly activation process with increased adsorption capacity and improved operationality and recyclability (Dias et al. 2007).

Fernandez et al. (2014) developed activated carbon from the biomass of orange peel using H_3PO_4 acid stimulation and successfully employed it to eradicate basic dyes such as Methylene blue and Rhodamine B from aqueous media. The batch and dynamic applications of the activated biomass material developed revealed a good adsorption capability for both coloring agents. While Mezohegyi et al. (2012) found activated carbon as an efficient means for employment in the removal of dyes from aqueous solution, Njoku et al. (2014) revealed it to be a very adaptable and cost-effective material for use in the decolorization process. Emami and Azizian (2014) make use of a unique agricultural waste, rambutan (*Nephelium lappaceum*) peel, and chemically aided KOH activation to make adsorbents in the form of activated carbon. The produced material was utilized to remove Acid Yellow 17 dyes, and the findings showed that it had high adsorbing power, even with elevated initial dye concentrations, with the Langmuir isotherm model being the best. The greatest monolayer adsorption capacity was reported as 215.05 mg g^{-1}. Using phosphoric acid as an activator, phosphate was used as a precursor to making activated carbon, which was effective in removing methyl orange from the aqueous solution (Ozer et al. 2012). Acid Blue 25 and methylene blue were removed more effectively using plum kernel-based activated carbon. The existence of calcium ions on the surface of activated carbon was found to have a significant impact on dye adsorption. While this discovery offers up new prospects for low-cost activated carbon manufacturing from agricultural leftovers, additional research is needed since the activated carbon generated may have different characteristics than activated carbon made from traditional raw materials. In this process, microwave irradiation used in the activation process serves as an appropriate alternative to furnace heating with a significant reduction in the operating cost. In addition to biomass, activated carbon can also be developed out of industrial wastes and scrap rubber tyres (Gupta et al. 2011). Waste rubber tyre-activated carbon might be a cost-effective, efficient, and quick way to clean dye effluent. A comprehensive evaluation on the production, categorization, and wastewater management application of activated carbon produced from sludge was published by Hadi et al. (2015). The adsorption capacity of activated carbon generated from sewage sludge is determined by texture along with the surface change and type of the functional groups found on the adsorbent surface. The column having activated carbon developed of paper mill sewage sludge was found efficient in removing Methylene blue and Reactive Red 24 from aqueous solution.

Low-cost adsorbents A number of pollutants are removed from wastewater using conventional activated carbon. Despite this, because of its intrinsic high cost, renewing activated carbon to enable for ongoing usage has a significant drawback, adding additional expenditures to the adsorption process. Polymeric materials and agricultural and industrial waste materials can all be used as low-cost absorbents. There are various advantages to using such materials, including inexpensive raw material costs since wastes are used, plentiful availability because wastes are created in vast numbers on a daily basis, and sustainability because renewable resources are used.

Polymeric materials

Polymeric materials offer great stability, processability, and a precise binding ability for target contaminants on utilization as a matrix (Alaba et al. 2018). As the materials are simple to malleablize and functionalize, they can be shaped to a considerably different configuration in order to improve their adsorption capability (Alaba et al. 2018). A substance that will be utilized to remove pollutants should have properties of being biocompatible with low toxicity, biodegradable, reusable, easy to synthesize, prepare, or extract, and should be affordable to use (Guerra et al. 2012). Many naturally occurring polymers such as cellulose, lignin, and alginate have been found to have these essential properties. For instance, alginate composites have a good ability to remove colors, heavy metals, and other contaminants from the water (Santoso et al. 2022). More than 90% removal efficiency can be achieved by making use of lignin-based compounds (Naseer et al. 2019). Cellulose-based polymers exhibiting a range of beneficial physiochemical and biological properties have been employed in the removal of heavy oils, fats, dyes, etc. (Peng and Guo 2020). Polymers are ranked as the best material for use in the environmental cleanup of different contaminants.

Agricultural residues and algal biomass

The leftover agricultural produce being rich in components such as cellulose, hemicellulose, and starch, exhibit extraordinary ability owing to their functional groups that facilitate better adsorption and as such complexation for metal ion contaminants (Jarre et al. 2021). One of the key benefits associated with use of these biosorbents is their easily adaptable nature at an industrial scale and high ability to get altered towards improving their adsorption capacities (Castro et al. 2021). When compared to conventional remediation treatments, these residues or their by-products are also more affordable, more effective, and produce less chemical or biological waste (Ghasemi et al. 2014). Ahmaruzzaman and Gupta (2011) make use of rice husk as low-cost adsorbent for use in the removal of contaminants from water and wastewater. The application of agricultural solid wastes as color adsorbents was also studied by Salleh et al. (2011). In addition to agricultural biomass, algal components are also employed for their role as dye adsorbent. Kousha et al. (2012) reported the use of red algae, *Jania adhaerens*, in the removal of Acid Blue 25. Compared to untreated forms, treatment of *J. adhaerens* with HCl and methanol enhances its ability as a dye remedial agent from 49.41 to 95.4% and 58.18%, respectively. The adsorption effectiveness was shown to be reduced by esterification, formaldehyde pre-treatment, and methylation. The dye adsorption capacity shows significant enhancement (from 35.62 to 71.05 mg g^{-1}) on subjecting to the reaction to propylamination.

Industrial wastes

Industrial wastes (like sludge, flue dust, lignin, fly ash, red mud, and blast furnace slag) are inexpensive, accessible, and effective, used for wastewater to extract contaminants (Ahmed and Ahmaruzzaman 2016). In wastewater, sludge has been shown to effectively remove Cd^{2+}, Cr^{3+}, and Pb^{2+} (López-Delgado et al. 1998), red mud can extract Cu^{2+}, and removal of $Cu^{2+}$and $Zn^{2+}$by organic acids (Nadaroglu et al. 2010). In case of dyes, traeolin (TP) and malachite green colors were removed from the aqueous solutions using *Ricinus communis* L. (castor bean presscake), a waste product from the production of biodiesel. Castor bean press cake has been proven to be an alternate low-cost adsorbent used for the extraction of colors from aqueous solutions due to its accessibility and effectiveness (Magriotis et al. 2014). An absorbent SBE (spent bleaching earth) was used for the removal of basic Red 46. The SBE came from leftovers from the processing of edible oils (Meziti and Boukerroui 2012). It underwent pre-treatment with the solution of ammonium chloride (NH_4Cl), heat treatment, and washing with HCl before being used as an absorbent. While VBE (virgin bleaching earth) has an absorption capacity of 84.03 mg g^{-1}, regenerate SBE has an absorption capacity of 73 mg g^{-1}. To increase removal efficiency, researchers often change operating parameters like pH, dosage, time of contact, temperature, and initial concentration of metal ions (Ahmed and Ahmaruzzaman 2016).

Magnetic absorbents

Magnetic adsorbents are used to remove the containments from the wastewater. This benefit has the potential to result in more cost-effective and efficient water treatment methods, which is one of the factors driving research into the use of different nanoparticles, magnetic particles, and nanocomposite in the removal of containments from wastewater (Ali et al. 2019). Iron oxides (hematite, magnetite, and maghemite) are effective when used as nanoparticles due to active sites, surface charge, surface area, and high redox activity (Maksoud et al. 2020). Majority of the magnetic nanoparticles are simple, deemed non-toxic, and (Maksoud et al. 2020) they can be created using a range of environmentally friendly techniques (Lagos et al. 2021).

Nanomaterials

Nanomaterials having a high surface-to-volume ratio and distinct optical, electrical, and magnetic properties have drawn a lot of attention in the years for use in the remediation of different contaminants (Gehrke et al. 2015). The nanostructures featuring vast and highly reactive surfaces and made cheaply have widely been applied in the treatment of wastewater (Zamora-Ledezma et al. 2021). Despite this, a shortage of knowledge regarding their toxicity and effects on the environment, and health, hampers their utilization to the fullest in the remediation of contaminants (Wołowiec et al. 2019). The current focus of bench-scale research and as such their application in the field for use in wastewater treatment is summarized as under:

Nanoparticles

The property of nanoparticles for use in the remediation of contaminants relies on their absorption property, their surface area, stability, and lower diffusion resistance. An external magnetic field can also be used to separate magnetic nanoparticles (Xu et al. 2013). Nanoparticles based on silicon, titanium, manganese oxides, and others are commonly employed as part of metal cleanup procedures. High porosity silica nanoparticles have surface silanol groups that are easily altered by silane chemistry. Silica nanoparticles may efficiently remove metal ions like Ni^{2+}, Pb^{2+}, and Hg^{2+} by themselves, in conjunction with compounds like GO, or when functionalized (Sheet et al. 2014). Heavy metals can be easily removed and separated using iron oxide nanoparticles (IONPs) owing to their strong redox potential, huge surface charge, and wider applicability (Bhat et al. 2022). IONPs with hydroxyl groups possess the ability to have their surfaces modified. Similar to silica, IONPs have the potential for use in the remediation of a range of heavy metals, and functionalization can enhance their adsorption ability (Al-Saad et al. 2012). Compared to their bulk counterparts, TiO_2 nanoparticles exhibit better catalytic capabilities. These nanoparticles exhibit the property to adsorb a series of metals and metalloids preferable being Cd^{2+}, As^{5+}, Cr^{6+}, La^{3+}, and Nd^{3+} (Kołodyńska and Araucz 2020). Many researchers revealed the potential of nanoparticles for removing colors from wastewater. Magnetic nanoparticles are the ones that carry the potential to successfully remove dyes from aqueous solutions. Magnetite nanoparticles developed from the waste of the iron ore tailings using acid leaching–precipitation and co-precipitation techniques have widely been used in the adsorption of Methylene blue and Congo Red dyes (Giriet al. 2011). Magnetite nanoparticles exhibiting 85% desorption indicate their ability to be reused on a broad scale to achieve remediation of dyes. Mahmoodi (2014) demonstrated the use of manganese ferrite nanoparticles made from manganese- and iron nitrate, in the removal of dyes preferably Acid Red18, Direct Red 31 and others from a binary system. Debrassi et al. (2012) observed magnetic nanoparticles to exhibit an adsorption power of 223.58, 248.42, and 144.79 mg g^{-1} on use in the remediation of Methylene blue, Crystal Violet, and Malachite green dyes. The repeated evaluation of the adsorbent revealed no influence on their adsorption performance, indicating high adsorption potential of the nanoparticles. On combining multiple substrates including chitosan, Fan et al. (2013) revealed them to exhibit the properties of its ingredients, including increased stability and adsorption capacity, and ease of separation. Methylene blue was effectively removed by the adsorbent. Additionally, non-magnetic nanoparticles have been used to remove colors from water. In a study, nano-sized aminopropyl functionalized magnesium phyllosilicate (AMP) clay was successfully employed in the removal of malachite green dye (Lee et al. 2011). On using 0.1 mg mL^{-1}, adsorption capacity peaks with a value of 334.8 mg g^{-1} indicating ~ 81.72% dye removal. The authors estimated that the use of 0.2 mg mL^{-1} of AMP is sufficient to achieve complete dye removal. Assefi et al. (2014) observed that activated carbon-mediated generation of cobalt oxide (Co_2O_3) nanoparticles with high adsorption capacity, efficiency, and cheap cost serves as an efficient tool for use in the removal of hazardous dye Eosin Y (EY) from aqueous solution.

Nanocarbon

A highly effective adsorbent such as carbon nanotubes (CNTs), graphene, and its derivatives is made of nanocarbon. The carbonaceous composition of CNTs along with their reactive surface area promotes direct interaction (covalent, hydrogen, and others) with contaminants in the water (Hasnain and Nayak 2019). As their hollow and rod-like nature provides several opportunities for adsorption, they are greatly being used for water cleanup. Capable of undergoing metal impregnation, and functional molecule/group grafting upon acid treatment, the surface of CNTs can be altered easily. The oxy-functional groups introduced by hydrochloric, nitric, or sulfuric acid functionalization are effective for use in the remediation of heavy metals such as cadmium, copper, lead, and mercury (Hasnain and Nayak 2019). By creating composite materials in the form of fibers, aerogels, etc., it is possible to transfer the properties of CNTs to the macroscopic world (Narvaez-Muñoz et al. 2019).

Graphene, one of allotropic forms of carbon, is another promising material for use in wastewater treatment (Anjum et al. 2019; Zamora-Ledezma 2021). A two-dimensional carbon nanomaterial called graphene oxide (GO) is created chemically by oxidizing a graphite layer. The adsorption process is impacted by the presence of functional groups on the surface of GO (Zare-Dorabei et al. 2016). The addition of functional hydroxyl and carboxyl groups to GO improves its adsorption capacity for use in the removal of heavy metals (Lingamdinne et al. 2016). GO differs from other nanomaterials like CNTs in two ways; Huge amount of heavy metal adsorption is possible in a single layer GO due to the availability of two-dimensional basal planes, and secondly, due to its straightforward synthesis procedure that may be completed by chemically exfoliating graphite without the use of a sophisticated instrument or a catalyst made of metal (Santhosh et al. 2016). Numerous studies on the use of nanoparticles based on graphene have been performed for use in the adsorption of heavy metals from wastewater (Zare-Dorabei et al. 2016). In a column reactor with GO enabled sand filter, Ding et al. (2014) and Anjum et al. (2019) while investigating heavy metal removal from wastewater found graphene and its other composite materials effective in the remediation of heavy metals from wastewater.

Membrane techniques

In the remediation process, membrane separation is one of the advanced technologies employed for use in the treatment of wastewater. In this process, wastewater is made to flow through a porous membrane. Solutes having larger size than size of the pore remain confined and the rest passes through the membrane. During the filtration process, confined solutes are constantly removed from the layer (Shindhal et al. 2021). The organic and inorganic pollutants, as well as suspended particles, can be eliminated with this form of treatment (Gunatilake 2015). Membranes can be categorized into (i) organic-made of synthetic organicpolymers (cellulose acetate or polyethylene) and (ii) inorganic-made of materials (metals, ceramics, silica, zeolites, etc.) (Gunatilake 2015; Shindhal et al. 2021). According to the driving force, membrane processes can be divided into three categories: osmotic pressure (such as in liquid membrane, electrodialysis, and direct osmosis), high pressure (such as nanofiltration (NF) and reverse osmosis (RO), and low pressure (such as distillation, microfiltration (MF), and ultrafiltration (UF) (Abdullah et al. 2019). RO, UF, NF, and MF are the primary techniques for extracting heavy metals and dyes from wastewater (Gunatilake 2015; Shindhal et al. 2021). RO membranes show excellent removal rate (99%) of metals and metalloid ions (Cu^{2+}, As^{+}, or Cd^{2+}) from waste-as groundwater (Bodzek 2015). Nanocomposite membranes can also produce great removal rates (~ 98%) when employed with water having metal and metalloid containments (like chromium, lead, cadmium, arsenic, and zinc) (Shukla et al. 2018). The RO and NF processes are utilized for the hydrolization of reactive dyes from wastewater, while as separation and recycling of indigo dye are carried out by UF. In most of the cases, MF's enormous size of pores prevents them from being used in the treatment of wastewater. The membrane filters employed separatively rely on a variety of factors (type of dye, composition of pollutants, dyeing process, etc.) (Shindhal et al. 2021).

Bioremediation of pharmaceutical compounds by microalgae and fungi

Microalgal remediation of PCs has recently gained scientific interest, as it is a solar-powered, environmentally robust, and long-term restoration technique (Xiong et al. 2018). Mixotrophic microalgae can flip from autotrophic to heterotrophic metabolisms given the availability of carbon sources and nutrients in the surroundings, allowing them to sustain and flourish in harsh conditions. Their flexibility makes them potential candidates for removing pollutants from wastewater (Kumar et al. 2010). The different processes used to remove the PCs are discussed as under:

Bioadsorption

PC bioadsorption by microalgae cells has been extensively documented. Diclofenac, ibuprofen, paracetamol, estrone, metoprolol, carbamazepine, trimethoprim, β-estradiol, and ethinylestradiol were among the PCs that were shown to be absorbed by microalgae at concentrations ranging from 0 to 16.7% (de Wilt et al. 2016). Moreover, it was found that *Scenedesmus obliquus* and *Chlorella pyrenoidosa*'s damaged cell biomass adsorbs around 10% of the accessible progesterone and norgestrel (Peng et al. 2014). Microalgae have negatively charged cell walls and contain polymers similar to cellulose, pectins, hemicelluloses, arabinogalactan proteins, extensin, and lignin. The main functional groups in microalgae cell walls are carboxyl, phosphoryl, and amine. Through electrostatic contact, pollutants containing cationic groups are aggressively drawn to the microalgal surface, resulting in efficient biosorption (Xiong et al. 2018).

Bioaccumulation

As documented in various publications, microalgae may bioaccumulate organic contaminants as well as growth nutrients. *Desmodesmus subspicatus*, for example, absorbed roughly 23% of radiolabeled 17α-ethinylestradiol (14C-EE2) in 24 h (Maes et al. 2014). The elimination of triclosan, trimethoprim, and sulfamethoxazole was found to be dependent on the bioaccumulation of micropollutants by algae (Bai and Acharya 2017). The studies showed that in the collection of carbamazepine, *Chlamydomonas mexicana* and *Scenedesmus obliquus* are the microalgal species plays a vital role (Xiong et al. 2016).

Biodegradation

The most efficient technique for microalgae to remove organic pollutants from an aqueous environment is by biodegradation. Microalgae enzymatically degrade complex parent chemicals to produce simpler ones. For example, *Scenedesmus obliquus* and *Chlamydomonas pyrenoidosa* showed that in an aqueous environment, progesterone was bioremediated upto 95% (Peng et al. 2014). In other studies, it is revealed that in urban or industrial wastewater, microalgae biodegraded 30–80% of pharmaceutically active compounds such as ibuprofen, caffeine, carbamazepine, and tris (2-chloroethyl) phosphate (Hom-Diaz et al. 2017) Microalgae can release different extracellular polymeric substances (EPS) into the environment including polysaccharides, enzymes, proteins, and lipids. By keeping extracellular enzymes close to the cell and enabling them to degrade various organic molecules, the moistened biofilm matrix produced by EPS acts as an external digestive tract (Flemming and Wingender 2010).

Use of fungi in the removal of PCs

Treatment of water samples contaminated with micropollutants especially pharmaceutical compounds, fungi has been demonstrated to be very effective (Silva et al. 2019). Their ability is to use nonspecific intracellular and extracellular oxidative enzymes to change a wide spectrum of refractory compounds (Silva et al. 2019). Although they are constrained by a protracted development cycle and spore production (Spina et al. 2012), Mycelial fungi's physiology and colonization techniques enable them to withstand the breakdown of complex organic compounds as well as fast changes in pH or humidity (Spina et al. 2012). White-rot fungi, members of the Basidiomycota phylum, have been investigated in various research works for their capability of removing medicinal contaminants from the water (Rodarte-Morales et al. 2011). The "white rot" name comes from the whitish look of the wood affected by these fungi as they remove the dark-colored lignin from the wood. These fungi are intriguing and desirable organisms for wastewater cleanup since they have the ability to break down lignin as well as a wide range of refractory pollutants, including pharmaceuticals, using the same method. They can mineralize a variety of pollutants because of their non-specific, non-stereoselective, and free-radical-based enzymatic process (Pointing 2001). Contaminant degradation appears to be mediated by either an external (lignin peroxidase, manganese peroxidase, laccase, and multifunctional peroxidase) or an intracellular (cytochrome P450 system) enzymatic system (Wesenberg et al. 2003). *Trametes versicolor* has been demonstrated to be efficient in the elimination of many medicines (Tran et al. 2010). For example, the elimination of ibuprofen, carbamazepine, and clofibric acid was investigated concurrently by the strains of *Ganoderma lucidum*, *Trametes versicolor*, and *Phanerochaete chrysosporium*, and *Irpex lacteus*. The findings revealed that the *Trametes versicolor* having cytochrome P450 system degraded carbamazepine and clofibric acid intracellularly (Marco-Urrea et al. 2009).

Conclusion

Water forms the core of the existence of humans and other living beings. Covering two-thirds of the earth's surface, its fulfillment of the requirement of humans has led to its exploitation to a considerable extent. The availability of clean water is greatly threatened by the release of pollutants from industrial settings, agricultural activities, and pharmaceutical companies, besides having a great impact of waste from household activities. They exert a strong impact on the portability and hygiene of drinking water that often progresses with a strong impact on human health, animals, plants, and on the life existing in the aquatic system. Pollution of the water bodies has not only threatened the survival of living beings but has left a severe impact on industrial development and on the environment. All this has created an urgent need to have methods to detect and control their levels to an extent that is considered safe for the survival of living beings and to the environment. For this, a proper understanding of the nature and properties of pollutants, their uptake rate and accumulation, and possible effects on living beings is to be understood so as to devise efficient and effective strategies to curb the problems associated with these contaminants. To mitigate any hazardous impacts, new advancements and ongoing monitoring of the execution methods of various programs and interventions related to industrial wastewater treatment are critically important. Research into the development of procedures that might cut down the consumption of water in industrial sectors and the development of effective and efficient water treatment systems is essential for the overall socio-economic progress and well-being of humans.

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Declarations

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