A review on emerging micro and nanoplastic pollutants, heavy metals and their remediation techniques

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Abstract: Plastics have become one of the most concerning pollutants today. They are non-biodegradable and potentially carcinogenic and lead to the generation of microplastics categorised as an emerging pollutant. Microplastics are plastic particles smaller than 5 microns in size. They are reported in various parts of the biosphere including human blood and tissues of various organs. Industrial and domestic effluents are two major contributing sources of microplastics in the ecosystem. A large volume of microplastics escape from the filtration processes of wastewater treatment plants (WWTP). This review studies the various removal methods for these pollutants in large-scale as well as lab-scale models and the present state of art facilities available to deal with it.

Keywords: Microplastics; Emerging pollutants; Heavy metals; wastewater treatment plant.

INTRODUCTION

With the constant industrial progress, new pollutants are being introduced into the environment. Emerging pollutants denote those pollutants which do not have any set standard limit or there are no regulations for monitoring these pollutants (Bell, 2011). The biggest problem faced with these pollutants is their impact on human health over a long period of time (Deblonde, 2011). Some of these pollutants include heavy metals, microplastics, pharmaceuticals and other persistent organic compounds.

MICRO/ NANO PLASTICS

Microplastics are defined as plastic fragments which are smaller than 5 mm in size. They are formed by the degradation of plastic and other synthetic waste disposed of in the ecosystem, mainly the lithosphere and hydrosphere. Microplastics are categorized into two parts based on the source of generation. They can enter the ecosystem directly, i.e., these plastic particles are originally produced in a size ranging from nanometres to micrometres. They are called primary microplastics and can be found in some industrial as well as domestic, cosmetics, and personal care products. Otherwise, they can be produced by the fragmentation and wearing down of bigger plastic pieces and are called secondary microplastics. They can form during the use or after the disposal of any plastic or synthetic product or textile (Kershaw, 2015) (Padervand, 2020).

Plastic production or usage has become an important part of today's industry with the packaging industry contributing the maximum plastic waste generation of around 141 million tonnes per year.

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The majority of the plastic products in the packing industry have a very small 'in-use' lifetime of 6 months or less hence, resulting in a large amount of waste production. Other major industries with a huge plastic waste generation are textile, consumer & institutional products, transportation, building, and construction, etc (Ritchie, 2018). These sources generally lead to the secondary microplastic formation. Run-offs of washed clothes made of synthetic fibres consist of microfiber of the textile which generally comprises polyester and acrylics (Browne, 2011). One of the dominant causes of the degradation of plastic materials into secondary micro/nano plastic is UV radiation by the process called photodegradation. This facilitates the oxidative degradation of polymers such as polyethylene, polypropylenes, and polystyrene (Jiang, 2018). These worn-down secondary plastic particles can no longer be broken down by the natural physical and chemical phenomena and stay suspended in the waterbodies they are discharged in.

The main source of primary microplastic entering the aquatic system is through domestic sewage discharge along with industrial effluents (Kershaw, 2015) (Murphy, 2016) (Padervand, 2020). According to research on effluents from 17 different facilities of the WWTP in the US for the presence of microplastics, it was estimated that over 4 million microplastics were being released into the water bodies by a facility in one day (Mason, 2016). Domestic sewage discharge has wash-offs of many cleaning and cosmetic products (Jiang, 2018) (Padervand, 2020). The raw materials of many personal care products and cosmetics consist of microbeads that act as scrubbing agents. These microbeads range from a few microns to a thousand micro (1mm) which are too small to be filtered out by WWTPs by even using the fine screen (1.5 to 6 mm). They absorb chemical pollutants on their surface and act as a vector or transport medium (Cheung, 2016) (Kershaw, 2015). Primary micro/nano plastic is used as an abrasive in cleaning products and they are also present in paints and coatings (Cheung, 2016). In industries, they are used as scrubbers to blast clean surfaces, in form of powder for moulding, and as feedstock for manufacturing plastic products (Jiang, 2018) (Kershaw, 2015). But there have been studies that state otherwise. According to (Carr, 2016), most of the microplastics present in the sewage are removed in the primary treatment zones and the secondary and tertiary treatment facilities minimally to the discharge of MPs into the water bodies.

The aquatic system is a major sink of microplastics. (Luo, 2019) highlights the fact that a higher amount of microplastic was found in freshwater bodies like rivers, streams, and lakes near cities which serve as the direct discharge site of most waste-water treatment plants than estuaries and seashores. They could also receive run-offs from landfills which might contain a significant quantity of microplastics. According to (Browne, 2011), microplastics were found on eighteen shores across six continents, and the abundance of the microplastic directly depends on the human population density of that place (Browne, 2011). (Woodall, 2014) states that a four-order magnitude of microplastic abundance was found in deep-sea sediments from the Atlantic Ocean, the Mediterranean Sea, and the Indian Ocean than in contaminated sea-surface waters. This shows how microplastics are transported across the aquatic system. Rivers and streams which serve as the direct sink of WWTP and industrial effluents have a maximum concentration of microplastic. Most MPs (some of the denser MPs settle in the river sediments) are then carried through the river system to bigger water bodies like seas and oceans. After spending some time being suspended in water, they settle on the sea and ocean beds with the heavier or denser MPs settling faster than the lighter ones (Luo, 2019).

Microplastics also enter the terrestrial system through the fragmentation of plastic and synthetic material left open to exposure to the atmosphere and sunlight (UV light increases the rate of degradation) (Kershaw, 2015). Open landfills, litter, or garbage disposed of by people in open are the examples of their sources. The sludge from the WWTP facilities which contains microplastics and microfibers of other synthetic materials becomes a pathway for MPs to pollute land (Rochman, 2018). Research states that the fauna of a place like earthworms, moles, mites, and other land-borrowing creatures also assists MPs to mix into the soil (Rillig, 2012) (Rochman, 2018).

Major raw polymers used in the plastic synthesis are polyethylene terephthalate (PET), polyurethane (PU), polystyrene (PS), polyvinyl chloride (PVC), polypropylenes (PP), polyesters, polyethylene (PE), polyamide (PA), and acrylic (Browne, 2011) (Padervand, 2020) (Ritchie, 2018). It also contains other additives in it to enhance its properties such as durability, flexibility, flame resistance, etc.

Plastics remain in the environment for a long time after being disposed off. Their high resistance

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to complete degradation makes it difficult to find an efficient method to manage and dispose off plastic waste. There are several instances reported where animals and marine creatures eat plastic materials mistaking them for food. This causes serious damage to their gastrointestinal tract and in severe cases even death. In the last 20 years, the record of the number of vertebrates that have plastic in their body has increased by 63% with the maximum seen in fishes and marine mammals followed by sea birds and marine turtles (Ryan, 2016)

Microplastics are as harmful as the bigger plastic waste. Microplastic, not only being toxic themselves but also act as a carrier of other toxic organic compounds which could accumulate in the consumer's body and cause serious health issues in the long run. Many additives like stabilizers, fillers, flame retardants, plasticizers, antioxidants, etc. are added to the plastic and microplastics during its manufacture to enhance its properties (Laskar, 2019) (Luo H. Z., 2020). Heavy metals like cadmium, copper, chromium lead barium and vanadium are present in the pigments and dyes used to provide color to the plastics. Organometallic compounds of barium are widely used as filler and compounds of lead are present in heat stabilizers, antioxidants, and UV stabilizers (Catrouillet, 2021). These potentially toxic unreacted monomers, oligomers, and chemical additives are leaked out from microplastics into the medium and this process of leaking is called leaching. (Luo H. Z., 2020) The ageing of plastic and microplastics increases the number of pigments and compounds being leached. Exposure to UV radiation, physical abrasion, chemical oxidation and biodegradation together result in the ageing of plastic and microplastics. The cracks and fragmentation of the MPs allows light and oxygen to reach the internal layer, accelerating the process. This increase in pigment leaching due to ageing was studied in simulated fluids resulting in fluorescence quenching of enzymes through binding interactions and forming pigment-enzyme complexes/flocs facilitating the further study of the potential risks of MPs (Luo H. Z., 2020). (Luo H. X., 2019) studied the leaching behaviors of fluorescent additives from polyurethane sponge microplastics in both natural and stimulated water and stated that the order of leaching is basic water > saline water > seawater > west lake > river > wetland. They also found that the number of leached additives increase with increase in the leaching time and the pH of the solution.

Microplastics being hydrophobic in nature with a high surface area to volume ratio tend to adsorb other organic compounds like DDT, hexachlorobenzene, polybrominated diphenyl ethers (PBDEs), endocrine disrupting compounds, pharmaceutical products, and other persistent and potentially toxic organic pollutants (Carr, 2016) (Jiang J. Q., 2018) (Laskar, 2019) (Padervand, 2020). They also adsorb some inorganic compounds which were observed to be more prominent in aged pellets than pristine pellets (El Hadri, 2020). The presence of some trace metals like iron, copper, zinc, arsenic, cadmium, tin, antimony, lead, and uranium has been seen on its surface. Microplastic also functions as a vector for the spreading of pathogens and microbes which has been explored (Kirstein, 2016). They found the presence of Vibrio spp. on the particles. Some of its animal pathogenic species are known to invade coral species causing coral bleaching. They also detected the presence of V. parahaemolyticus on them which is known to cause water-borne diseases in humans. Microplastics provide a suitable surface to the rapidly multiplying bacteria leading to complex biofilms buildup of many organisms on its surface. These biofilms being of a highly heterogenous nature provides many ecological advantages like a protective barrier, accumulation of nutrients, and mechanical stability thus, providing a suitable colonizing ground for many harmful pathogens. The growth of harmful algae was also observed in these biofilms.

In a study (Lei, 2018) conducted to demonstrate the toxicity of microplastics, zebrafish *Danio rerio*, and nematode *Caenorhabditis elegans* were exposed to a microplastic mixture containing polyamides, polyethylene, polypropylene, polyvinyl chloride, and polystyrene. They found that microplastics of size ~70 micrometres caused intestinal damage with cracking of villi and splitting of enterocytes. On exposure to 5 mg/m^2 microplastic for 2 days, they observed induced lethality and reproductive dysfunction along with the reduction in calcium levels and increase in oxidative stress genes in *C. elegans* which were all dependent on particle size. Hence, proving the fact that the toxicity depends both on the size as well as the composition of these microplastics. Its accumulation has been found in the livers, gills, and gut of zebrafish (Lu, 2016). The presence of cellophane and polyester fibres along with an abundance of many toxic trace metals like chromium, cadmium and lead was discovered in Pacific oysters, seafood that is eaten worldwide(Zhu, 2020). They found that cellophane tends to accumulate in the gills, mantle and muscles of the oyster whereas polyesters were seen to accumulate in its digestive glands. This also highlights one of the major issues of bioaccumulation, the transfer of these toxic substances to other organisms and humans and its biomagnification through the food web. Microplastics also increase the dissolved organic matter of water due to their presence (Çobanoğlu, 2021) states that genomic instability in human peripheral lymphocytes was caused by polyethylene lymphocytes. Increased exposure to polystyrene nanoparticles increased the damage to the DNA of human monocytes, polymorphonuclear cells, and fibroblast hs27 cell line. Constant exposure to microplastic for a long time contributes to genomic instability and an increase in DNA damage which may result in infertility and cancer (Çobanoğlu, 2021) (Laskar, 2019).

REMOVAL METHODS OF MICRO/NANO PLASTICS

1) Wastewater treatment plants

The wastewater treatment plant incorporates various standard and advanced methodologies for the mandatory treatment of municipal and small industry wastewater before releasing it into larger water bodies. The WWTP can act as the most effective barrier of microplastics as well as one of its major entry routes into the aquatic system. Sewage entering the WWTP carries huge amounts of microplastic particles and microplastic fibres originating from the wash of various personal care products and wash-offs from laundry as discussed previously. The various physical, chemical and biological treatment steps of the plants remove almost 97.4% to 98.4% of the total microplastic present in the sewage and wastewater entering the WWTP (Lares, 2018) (Talvitie, 2017). Around 97% of the total filtered microliter was removed in the primary or pre-treatment. This step consists of screening, grit removal, and chemically enhanced primary sedimentation (Talvitie, 2017). The main aim of the primary treatment is to selectively remove the settable organic and inorganic solids and particulate matter by sedimentation of the dense materials or skimming (scumming) of lighter floating materials (Gurung, 2014). In case bar screens for the screening process, they have a large space between their bars of around a few millimetres which proves ineffective in removing microlitter with sizes ranging from a few microns The shape, size, and density of the microplastics influence their removal through floatation or sedimentation(Bilgin, 2020).. The flotation removal process occurs at a small hydraulic retention time with turbulent mixing of wastewater by air bubbling and is effective in removing the less dense, floating MPP and MPF. Whereas, sedimentation has a long retention time with little to no turbulence. It has been reported to outperform the flotation process for capturing and removing a majority of the microlitter. Hence (Bilgin, 2020) emphasizes on to make the sedimentation process the primary focus for improvement. They strongly suggest investing resources in building gravity-based settling units like grit chambers and installation of inclined plate or tube settlers in existing settling tanks in WWTP. The addition of suitable coagulant into the wastewater also helps in better settlement of particles and colloids.

The secondary treatment step includes the biological treatment processes in which microorganisms are allowed to grow which are responsible for the decomposition of biodegradable waste present in the sewage. The activated sludge process is one such widely used secondary treatment process. The microorganisms are suspended in the wastewater with the help of suitable mechanical means. It allows the formation of flocs which are then removed by the gravity-settling process (Gurung, 2014). This reduced the microlitter upto 7% to 20% range (Talvitie, 2017). The effluent further undergoes tertiary treatment and filtration through a biologically active filter (Talvitie, 2017) suggest that BAF doesn't prove to be inefficient in removing microplastic and the efficiency of the whole removal process depends on the efficiency of the primary step. (Nakazawa, 2021) reported that coagulation-flocculation, sedimentation, and rapid sand filtration were able to remove some microplastics but it was comparably less to the membrane technology which is effective in removing almost all the microplastics.

The microlitter is removed from WWTP with effluent or dried sludge. The digestion of organic matter proves ineffective for non-degradable or slowly degrading particles like microplastics. This microlitter may also be recycled inside the plant in form of rejected water used to dewater raw and excess sludge. Around 20% of the previously filtered microlitter returns to the initial treatment process through the rejected water. The rest 80% of it is present in the dried sludge which finds its way into the ecosystem in form of compost used in farming.

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Although the WWTP can remove a majority of the microplastics with the effluent containing only 0.7 to 3.5 microlitter particles per litre of treated effluent. Still, considering the enormous volume of effluent, this is a huge amount. According to (Talvitie, 2017), around 2.0 x 10^8 to 7.9 x 10^8 microplastic particles are released into the Baltic Sea per day through the treated effluents. Other studies (Kershaw, 2015), (Mason, 2016), (Murphy, 2016) and (Padervand, 2020) also suggest that the huge amount of microlitter and microplastics enter the aquatic system through effluents of secondary or tertiary WWTP.

2) Membrane technology

Advancement in membrane separation technology has led to the development of the key functions of advanced WWTP processes. Its combination with bioreactors can be stated as one such innovation. A membrane is a thin semi-permeable physical barrier or filter which separates particulate matter and contaminants from wastewater, allowing a relatively clean effluent to pass. The membrane bioreactors (MBR) are stated to be capable of reducing microplastic concentration from 6.9(±1.0) to 0.005 (±0.004) MP per litre. Though it is generally used in the tertiary stage of advanced WWTP, (Talvitie J. M., 2017) states it can be used in the primary stage too but this may lead to more fouling of the membrane. The finest MBR filter had the smallest pore size of 0.4 microns (Talvitie J. M., 2017). Membrane technology has proven to be a better alternative to the conventional WWTP process (Gurung, 2014). Though its high efficiency of almost 99% of microplastic particle removal, (Bayo, 2020) states that microplastic fibres could bypass the MBR filter under high pressure.

Membranes can be grouped on basis of their pore size, the material used, texture, driving force, etc. It can be classified as microfiltration, ultra-filtration, nano-filtration, and reverse osmosis based on the size of the separated solid particles by the membrane. Micro-filtration and ultra-filtration are used generally used in the MBR system due to their larger pore size which reduces fouling of the membrane whereas, nano-filtration and reverse osmosis are used for the final purification process where the amount of solid contaminant is relatively less and thus doesn't lead to quick fouling of the membrane. There are various factors that affect the filtration process such as membrane resistance, hydrodynamics between liquid-membrane interface, fouling and backwashing of the membrane, and its degradation over time. Membrane fouling is one of the major problems in membrane filtration technology due to the deposition of solids, a thick cake of residue forms on the membrane hindering the filtration process. It blocks the pores of the membrane, thus reducing permeability and increasing the flow resistance of the effluent. Backwashing has to be done at regular intervals to remove fouling (Gurung, 2014). Along with being a very expensive process, this process also causes membrane pollution when the old and damaged membranes are disposed off (Stephenson, 2000) (Wang, 2021). The organic membrane may be polymer or cellulose-based such as polysulfone, polyacrylonitrile, polypropylene, acetylcellulose, etc. Inorganic membranes made of ceramics, aluminium, high-grade steel, glass, and fibre-reinforced carbon may also be used which are more heat and chemical resistant than organic membranes. Depending on all the above-discussed factors, its operational parameters such as flux, transmembrane pressure, etc are determined. Submerged MBRs are commonly used in WWTPs due to their high compatibility with the activated sludge process. It also has the advantage of small footprint reactor and compactness in design, low energy consumption, and low transmembrane pressure. Its membrane can either be hollow fibre membranes or flat sheet or plate-like (Gurung, 2014). Transfer flow modules that use hollow fibres consume less energy. MBR can also be used to recover valuable components from effluent (Stephenson, 2000).

Along with the removal of microplastics, MBRs are also effective in the removal of advanced levels of organic and suspended solid particles but their biggest drawback is the requirement of expert design and skilled workers.

3) Dissolved air flotation

A study shows that microplastic can be removed by positively modified dissolved air flotation (Wang, 2021). They reported that the conventional dissolved air flotation was not ideal as it removed only 32.7% to 48.7% of the microplastic due to electrostatic repulsive between the microbubbles and the microplastics. On addition of cetyltrimethylammonium bromide and poly (diallyldimethylammonium chloride) reduced this repulsion and created an adhesion between the microbubbles and microplastics. This significantly increased the removal efficiency by 32% for PE, 33.7% for PET, and 13.6% for PA. This is a safe method to substitute membrane technology thus reducing membrane pollution.

It aims to remove total suspended solids (TSS), biochemical oxygen demand (BOD), and oils and greases (O&G) from a wastewater stream coming from various oil refineries, petrochemical and chemical plants, natural gas processing plants, paper mills, general water treatment and similar industrial facilities.

4) Coagulation

The process of coagulation and flocculation has been used for a long time for the removal of the suspended particles. Magnetic magnesium hydroxide was found to have a higher efficiency than the traditional magnesium hydroxide as a coagulant to remove polyethylene microplastic floating on the water surface (Zhang, 2021). The maximum efficiency of 87.1% was achieved when the ratio of Mg^{+2}: OH was 1:1. This efficiency can be increased to 92.6% by adding 200mg/L magnesium hydroxide, 120 mg/L of Fe_3O_4 and 4 mg/L of PAM. In the growing problem of microplastic and microlitter pollution, a sustainable, efficient and cheap method for removal has become very important. Removal of microplastics using coagulation is considered a cost as well as an energy effective process. (Xu, 2021) provides a detailed report on the process of coagulation, types of coagulant and the selective contaminant removal. They also discussed the environmental conditions which could affect this process. (Ma, 2019) studied the removal efficiency of polyethylene by Al- and Fe-based coagulants and they found that Al has a higher efficiency than Fe salt. They found that smaller size of particles were better removed than larger counterparts. The addition of anionic PAM enhanced the removal process due to better floc formation. These flocs can be easily separated using ultra-filtration.

5) Novel materials for microplastic removal

The need for a better, more efficient and eco-friendly way of removal of microplastics has become an important focus for developing new water treatment materials. These materials can be organic and biodegradable plant-based materials or inorganic materials or a hybrid consisting of both organic and inorganic components. Wang J. S., 2021 synthesized magnetic biochars modified with magnesium and zinc respectively. They observed that Mg-modified biochars adsorbed 98.75% and Zn-modified biochars adsorbed 99.46% of polystyrene micro-spheres of 1 micron. They choose micro-spheres of 1 micron as they easily passed the barriers of WWTP and can cause serious damage to aquatic organisms. They stated that through pyrolysis, the modified biochars can be regenerated and microplastics can also be degraded. The efficiency of the biochar was high even after 5 cycles of adsorption and pyrolysis. Similar to magnetic biochars, magnetic carbon nanotubes (Tang, 2021) were used for removing micro plastics.

(Shen, 2021) conducted studies on aluminosilicate filters and stated that on modification of the filter by cationic surfactant, its efficiency to remove microplastics became greater than 96% and reportedly was higher than that of rapid sand filter. (Sun C. W., 2021) and (Sun, 2020) synthesized sponge material from a chitin and chitin-graphene oxide mixture. Both the sponges are reusable, biodegradable, and highly efficient in removing microplastics though the presence of graphene oxide results in a slower degradation rate than just an unmodified chitin-based sponge. (Sun C. W., 2021) also stated that the addition of graphene oxide, O-C_3N_4, and graphene oxide with carboxymethyl cellulose is capable of removing microplastics with substituted functional groups like carboxylate-modified polystyrene and amine-modified polystyrene. They concluded that it was due to the electrostatic interaction, hydrogen bond interaction and pi-pi interaction between them.

A highly porous sponge material has been fabricated from plant protein by (Wang Z. S., 2021). They cross-linked oat proteins to form a highly interconnected pore structure that has high mechanical strength and elasticity with a microplastic removal efficiency of 81.2% (Wang Z. S., 2021). It is reusable and its efficiency remains very much the same even after 20 cycles being a plant-based product, it is completely biodegradable. (Cunha, 2020) found that freshwater microalgae Cyanothece species released an extracellular polymeric substance that has a high bioflocculant activity for low concentrations of microplastics. With constant research and improvisation, the potential to find a novel, eco-friendly, efficient, and reusable material to replace the conventional and even hazardous water treatment process is always large.

6) Other methods

Microplastic removal and degradation has been studied with many microorganisms and living creatures. (Silva, 2021) gives an elaborate report on the use of microbes like fungal genera Aspergillus and Penicillium and bacterial genera Pseudomonas and Bacillus in the degradation of the microplastic by their enzymatic action. (Padervand, 2020) also states various other such biological methods of removal like adsorption and digestion of microplastics by various aquatic organisms though they can potentially harm the organism and are not recommended.

Photodegradation is another method that can be used to control microplastic pollution. It is effective for the degradation of persistent organic compounds also. It is an advanced oxidative process that involves the use of photocatalysts and light irradiation to generate active groups to convert the microplastics into carbon dioxide and water. These active groups include ·OH, $\cdot O^{2-}$, and hole (*h*+). Some of the photocatalysts that degrade microplastics are TiO_2, ZnO and BiOCl. An insightful description of these photocatalysts and their application has been provided (Xu, 2021).

HEAVY METAL CONTAMINANTS

According to (Duruibe, 2007), heavy metals in general collective terms refer to the group of metals and metalloids with an atomic density greater than 4 g cm^{-3} or 5 times or greater than that of water. It is not the density but its chemical properties which make it a great source of concern. These elements include chromium, copper, iron, zinc, mercury, lead, arsenic, cadmium, etc. Some of them like iron, zinc, manganese, etc are biologically important for the proper functioning of the human body and are consumed through foods, drinks or additional supplements. Their consumption above the recommended level leads them to biotoxic effects. Metals like mercury, lead, arsenic and cadmium are highly toxic even at an extremely low level. The concentration and oxidation state of heavy metals can determine their bio-importance or bio-toxicity. In the case of biotoxic metals, they form stable complexes through exchange and coordination mechanisms with the essential proteins and enzymes thus, hampering the vital functions of the body (Duruibe, 2007) (Iqbal, 2009)(Jaishankar, 2014)(Patrick, 2003).

Heavy metals are persistent contaminants and cannot be degraded and destroyed. They enter into the biosphere either through natural or anthropogenic sources, the latter being the major contributor. These heavy metals can be present in both elemental and organic or inorganic compound forms.

Mining is one of the biggest sources of this pollution. Metal contaminants produced by 5 to 15 years of mining hard rocks can persist for hundreds of years after the cessation of the mining process (Duruibe, 2007). They are also released into the environment through open dumps, industrial products and by-products, traffic, and automobile exhaust. After the elemental or compound metal pollutants are exposed to open surroundings, they get washed off by acid water (coming from water bodies or rain) which carries them into the soil thus polluting it. This can also carry them to the underground water table or the nearby water body (Duruibe, 2007) (Iqbal, 2009). The plants growing in this soil, the animals feeding on these plants and the aquatic creatures thriving in the polluted water body then consume these heavy metals which get stored in their tissues. They then enter the human beings dependent on these contaminated plants, fish, animal products and water bodies for their daily lives. People such as miners, industrial workers, and cleaners are at a higher risk of heavy metal poisoning due to direct exposure to these toxic contaminants (Patrick, 2003).

The biological effects of heavy metal pollution can be acute, chronic or sub-chronic in nature along with being neurotoxic, carcinogenic, mutagenic and teratogenic. They lead to gastrointestinal disorders, diarrhoea, vomiting, tremor, haemoglobinuria and cause respiratory problems such as coughing and pneumonia when their volatile fumes are inhaled (Duruibe, 2007) (Jaishankar, 2014) (Patrick, 2003).

Lead is a common pollutant found in automobile exhaust, artist's paints, mirror coatings batteries, etc. Lead poisoning causes dysfunctions in the kidneys, joints, reproductive systems, and cardiovascular and inhibits the synthesis of haemoglobin. They also cause acute and chronic damage to both the central and peripheral nervous systems. A study has found a lead to retard the growth of grey matter in the brain in children thus resulting in poor intelligence quotient (Duruibe, 2007) (Jaishankar, 2014) (Patrick, 2002).

Mercury unlike zinc, magnesium or manganese has no biological importance in the body. It is commonly used in thermometer bulbs, disinfectants, anti-fungal agents and organo-metallics. It causes congenital malformation and gastrointestinal disorders like corrosive oesophagus and haematochezia. The leached mercury compounds are converted into more readily absorbed organic forms such as monomethyl and dimethylmercury by bacterial actions. Minamata disease discovered in 1956 in Japan is an example of severe mercury poisoning. This epidemic was caused by the release of methylmercury and mercury sulfate into the nearby water body by a chemical factory, which then bioaccumulated and biomagnified in the fish and other seafood consumed by the residents causing over a thousand deaths (Duruibe, 2007) (Jaishankar, 2014).

Arsenic, another highly toxic heavy metal and potential carcinogen causes coagulation of protein and inhibits the production of ATP (adenosine triphosphate) by forming stable complexes with coenzymes during respiration (Duruibe, 2007) (Jaishankar, 2014) (Mandal, 2002).

One of the major problems faced in the whole process of heavy metal removal is the accurate and precise assessment of these heavy metals in the collected samples. Due to a very small concentration in the collected water sample, the assessment technique may fail to detect its presence in the water body thus not proceeding further in the treatment procedure. This shows the urgency in developing an accurate, precise, efficient, and cost-effective assessment technique.

REMOVAL METHODS OF HEAVY METALS

One of the biggest problems faced in heavy metal removal treatment is the lack of precise tools and procedures for the accurate assessment of heavy metals in a given sample. Bibliometric or scientometric analysis based on statistical methods is assumed to be a promising tool for this purpose.

Three of the most used technologies for the removal of heavy metals are (a) physicochemical processes (b) electrochemical technologies and (c) advanced oxidation processes. It can also belong to a subdivision which is a combination of two or more processes.

1) PHYSIOCHEMICAL PROCESS: The physicochemical process includes adsorption, chemical precipitation, ion exchange, membrane technology and others. Out of these, the bibliometric analysis showed that adsorption is the most discussed method. Some of the very common adsorbents are carbon-based adsorbents (like activated carbon, carbon nanotubes, and graphene), chitosan-based adsorbent, mineral adsorbent, magnetic adsorbents, and bio-sorbents. The removal efficiency is directly influenced by factors such as pH, heavy metal concentration, temperature, the ratio of heavy metal to other ligands, and ionic strength along with the absorbent's exclusive properties which make its removal capabilities different from other adsorbents.
   A) CARBON-BASED ADSORBENTS: they act as good adsorbents because of their high surface area. Its properties can be enhanced by the addition of functional groups on its surface which leads to more sites for heavy metal adsorption. Nitrogenation, oxidation, and sulfuration are some of the most used modification techniques of carbon-based adsorbents. They may also be used to improve its other properties such as thermal stability and mechanical strength. High carbon sources can be easily derived from agricultural waste such as rice husks, olive stones, corn straw, and others for the production of activated carbon adsorbents but what makes this process expensive is its modification process which involves high heat/pressure, strong acids/bases or complicated oxidation/reduction reactions. Carbon nanotubes are highly efficient materials with physical and chemical stability and mechanical and magnetic properties. They are expensive and are also harmful to the environment. Hence, they are held back to lab-scale production, application and testing.
   B) CHITOSAN-BASED ADSORBENTS: They are natural adsorptive polymers that are biodegradable and non-toxic to nature and organisms. Their low mechanical strength, poor stability, low porosity, surface area and high crystallinity make them difficult to work within their natural state. Hence, they also require modification through cross-linking and grafting which adds covalent chains between the polymer backbone and functional group and help in the addition of the functional group to the chitosan backbone respectively.
   C) BIOSORBENTS: The adsorption of pollutants on the surface of the cell is called

biosorption and its mechanism is very similar to that of normal adsorption methods. The presence of functional groups like aldehyde and carboxylate is the site for the pollutant's adsorption. These interactions can be electrostatic, complexation or oxidative/reductive in nature. They can bind through aggregation, ion exchange, or micro-precipitation. One of their biggest advantages is their biodegradable and non-toxic nature which is cost-effective and efficient in the process. Biosorption is a very effective process that is used commercially due to its ability to heavy metal removal in very low concentrations.

D) INORGANIC, MAGNETIC, AND METAL ORGANIC FRAME ADSORBENTS: They include various mineral adsorbents like zeolite, clay or silica. The basic interactions taking place in them are physical or chemical adsorption or ion exchange. Clay's high cation selectivity and exchange capacity combined with high swelling index and surface hydrophilicity and surface electronegativity make it a great adsorbent. The use of natural minerals is cost-effective but the efficiency of heavy metal removal decreases after a few uses. Modification by calcination, impregnation, or grafting can improve its properties.

E) MAGNETIC ADSORBENTS: They are adsorbents with a specific material matrix that has iron particles like nanoparticles of ferric oxide. The base matrix can be carbon, starch, polymer or biomass. They are low-cost, easy-to-synthesize materials with high surface charge and reusability. When the base material is made of starch, biomass or any biodegradable polymer gives them bio-decomposable properties.

2) MEMBRANE-BASED FILTRATION AND SEPARATION: it consists of many technologies, some of which are stated below.

A) ULTRAFILTRATION AND MICROFILTRATION: The pores of ultrafilters are larger than the size of the heavy metal ion and so they can not filter them unless they are in an aggregated or colloidal state. There are two methods by which this is done. (a) polymer enhanced ultra-filtration (b) micellar enhanced ultrafiltration. In the case of polymer-enhanced ultrafiltration, additives such as polymeric ligands are added which form an electrostatic bond with the metal ion and prevent them from passing through the filter pores. Polyacrylic acids, carboxyl methylcellulose, and polyvinyl ethyleneimine are a few examples of these polymeric ligands. The high removal rate of heavy metal ions, reusability of ligands, and lower operation cost are some of the advantages of these processes. Whereas in the case of micellar enhanced ultra-filtration, cationic and anionic surfactants are used for complexation of the heavy metal ions which stick together and form a composition of bigger mass. Sodium dodecyl sulfate and rhamnolipid are some examples of these surfactants.

Microfiltration is an effective process for the removal of micron-sized particles like microplastics, viruses, drugs and other organic pollutants. It has a low efficiency when it comes to the removal of heavy metals. This is because its pore size is much larger in comparison to the heavy metal particles.

B) NANOFILTRATION: ultra-filtration and micro-filtration processes are dependent only on the size-exclusion principle which means the pollutants were removed based on their size and the pore size of the filter. But the nano-filtration process involves other parameters like membrane chemistry and configuration, pH, pressure, temperature, and feed concentration. Nano-filtration membranes have electric charges on their surface so it is capable of attracting and holding on to the oppositely charged heavy metal particles. It was stated that the removal efficiency of nano-filters depends on the size and charge of the filter. The removal efficiency of more than 99.2% for heavy metals like arsenic, copper, and cadmium using nano-filters made of polyamidoamine.

C) REVERSE OSMOSIS: This is a pressure-driven process where the applied pressure is maintained more than the osmotic pressure of the feed solution across a semi-permeable membrane. It is a highly efficient process for the removal of heavy metals but it is also very expensive and its membrane is not back-washable.

D) ELECTRODIALYSIS: It is the process where the ions are separated using electric potential difference. A series of alternating cation exchange membranes and anion exchange membranes are arranged parallel to each other. Electric potential difference is applied across them so that the cation passes through the cation exchange membrane and the anion passes through the anion exchange membrane. The electrodialysis process has a high-water recovery with no chemicals involved and no reaction and no phase change occurs. Still, membrane fouling is observed in this process. The ion exchange membrane is expensive and their regular changing due to fouling can make this process very expensive.

3) CHEMICAL REMOVAL METHODS: they involve processes like precipitation, coagulation and flocculation, and flotation with the help of chemical reagents.
   A) CHEMICAL PRECIPITATION: In the chemical precipitation method reagents like lime, other hydroxides, or sulfide precipitates are used to convert the dissolved metal ions into solid particles which precipitate at the bottom of the container. Hydroxide precipitates are broadly used because it is easily available, less expensive with a tunable pH and on combining with metal ions form insoluble metal hydroxides. It is a widely used method in water treatment industries due to its ease of operation, easy availability and cost-effectiveness but they lead to the generation of by-products like sludge.
   B) COAGULATION: Coagulation helps in destabilizing the colloidal particles by neutralizing the forces present between them whereas flocculation helps in the agglomeration or gathering up of these destabilized particles to form flocs which then settles down at the bottom. Aluminium or ferrous sulfate and ferric chloride are some commonly used or traditional coagulants and poly-aluminium chloride (PAC) and polyacrylamide (PAM) are some examples of flocculants. Many heavy metals like arsenic, selenium, chromium, lead, etc. can be easily and efficiently removed by this process but it leads to a large sludge generation which sometimes can be toxic and hazardous to health. Other disadvantages of this method include it being selective for some metals. The traditional process may also prove to be inefficient for emerging contaminants like microplastics and hence needs further study and modifications.
   C) FLOTATION: Flotation involves the passing of microbubbles through wastewater to remove various metal ions. Dissolved flotation, ion flotation and precipitation flotation are some ways in which this technique is used. In the dissolved flotation process air or gas is passed through the wastewater through a pump that generates microbubbles. The metal ions get attached to these microbubbles and form low-density flocs or agglomerates which rise to the surface from where they are skimmed and removed. In the ion precipitation method, the hydrophobicity of the metal ions is increased by the addition of surfactants which are then removed by air bubbles. Precipitation flotation also makes use of air bubbles like the above two processes but chemical precipitates are used in this process. It consumes a shorter time to efficiently remove the metal ions compared to the other. Overall, flotation is an effective and compact process for the removal of heavy metal rapidly at a moderate cost. Some major drawbacks arise when using ion flotation. It is inefficient when the amount of heavy metal contaminants is less and the amount of wastewater is very large. It also depends on surfactants which act as the collector of contaminants hence a non-toxic and eco-friendly surfactant has to be used which has a strong collection ability, good selectivity and easy construction.

OTHER CONTAMINANTS

1. Nitrates and phosphates

Nitrates and phosphates are two essential nutrients and natural parts of an aquatic system. They are very important for the growth of algae and aquatic plants on which the aquatic creatures depend for food and shelter for survival. Hence, the absence of these nutrients can lead to the disruption of the whole food web of the aquatic system. But excess of these nutrients has led to eutrophication and nutrient pollution which acts as a serious threat to aquatic life.

Their sources can be both natural and anthropogenic. Atmospheric nitrogen oxides can react with water to form nitric acid to fall as acid rain seeps into soil to form various nitrogen compounds. Whereas, phosphates can enter the system from the breakdown of rocks and minerals. Dead decaying organisms along with animal/plant wastes are also some natural sources of nitrates and phosphates. Anthropogenic sources include the washed-off fertilizer from fields into nearby water bodies such as rivers, ponds, lakes, etc. Other major sources are animal manure and chemical fertilizers used in agriculture, direct discharge of sewage into the water without prior treatment, etc. Many times, certain soaps and detergents also contain nitrogen and phosphorus compounds which lead to this pollution.

Their excess in water causes a rapid overgrowth of algae in the waterbody called an algal bloom. This reduces the amount of dissolved oxygen in the water for other living aquatic creatures to survive. The oxygen deficiency leads to the death of aerobic living beings and they are replaced by anaerobic microbes and algae which many times are toxic. Getting in direct contact with these toxic algae could lead to rashes. Drinking water from such waterbody could lead to stomach illness. When disinfectants used in water treatment come in contact with such toxic algae, harmful chemicals named dioxins are released. Ingestion of nitrate and phosphate-contaminated water is very toxic in itself.

Water with excess nitrate is reported to be very harmful to infants and pregnant women. It causes methemoglobinemia, also known as “blue baby syndrome” in infants. The various forms that nitrate converts to like nitrite and nitrosamine are more lethal than its nitrate form, directly affecting the oesophagus and pharynx. Prolonged intake of nitrate contaminants is carcinogenic, causing prostate and gastrointestinal cancer. Excess phosphates damage the kidney and lead to osteoporosis. According to Environmental Protection Agency (EPA), the recommended value of phosphorus in drinking water is 5mg/L (Singh, 2013).

Removal methods

There are many developments for the removal of nitrates and phosphates from wastewater and effluents. The most recent approaches in removal techniques include ion exchange chromatography, reverse osmosis, and electrodialysis but these processes are very complex and high cost. There exist cheaper and more efficient alternatives for them which are generally categorized into adsorption methods, chemical methods, biological methods, and nanotechnology. The chemical process uses iron, aluminium, lime, calcium or magnesium ion to react with the soluble salts to form insoluble clots which then settles down at the bottom. This process is called chemical precipitation. Maintaining the pH and temperature are essential requirements for this process. Generally, this method does not require waste disposal but it requires post-treatment due to the formation of by-products.

The biological treatment process involves denitrification using microbes which can either be autotrophs or heterotrophs. Pseudomonas, Micrococcus, Achromobactin, and Bacillus are some examples of denitrifying microbes. In this process, the nitrate is taken by the denitrifying bacteria as a terminal electron acceptor in the absence during the respiration process. As a result of this process, the inorganic nitrogen compound is reduced to harmless nitrogen gas. It is very effective in the treatment of large quantities of water like in the treatment of sewage and wastewater as it is very efficient, environment-friendly, and cost-effective. (Velusamy, 2021) has discussed the various factors affecting this procedure.

Adsorption techniques include the use of powder-activated carbon, carbon cloth and nanotubes, commercial activated carbon and granular activated carbon treated with zinc chloride. This procedure is considered the best technique for WWTP not only because of its simple design, convenience, cost-effectiveness and ease of operation but also for its applications in the removal of multiple inorganic anions other than nitrates. Some of these are fluorides, bromates, and perchlorates. These adsorbent materials can be made from natural materials like biochar derived from sawdust and rice husk. The by-products derived can then be used as potential fertilizers loaded with nitrogen and phosphoric compounds. (Velusamy, 2021) also lists other natural materials that can be used as adsorbents on modifications. They also provide a detailed report on various nanoparticles and nanocomposites which are effective nitrate and phosphate removers from water.

2. Oil spills

Oil spills and leakage is another source of pollution especially in channels, seas and oceans. They are generally spilt due to accidents caused during their mining from sea beds or during their transportation through the sea routes. These hydrocarbons are very hard to degrade and continue to float or remain suspended in the water body for a long time (Blumer, 1969). (Nelson-Smith, 1971) states that around 22,000 tons of oil were released into the aquatic system between 2010 to 2013, 48% of which were petroleum-derived fuels. It also accounts for the major oil leaks till 2019. (Nelson-Smith, 1971) has provided a detailed report concerning the various environmental hazards oil spills impose. Many sea birds which dive into the water for their food have been reported to be covered in a layer of oil that destroyed the water-resistant nature of their wings, reducing their buoyancy and leading them to not able to fly anymore and drown. (Nelson-Smith, 1971) has also provided an elaborate discussion on the various harms caused to aquatic life due to oil spills.

Removal methods

Various methods and applied technologies based on insulation and oil gathering with the addition of dispersants, solidifiers, bio-reducing agents, and in-situ burning of dispersed fuel. These methods are seen to be inefficient, expensive, and can produce secondary pollutants. (Oliveira, 2021) discusses the various sorbents application which has proven to be more effective and cost-efficient. It has the properties of recovering lost oil and regeneration and reuse properties. Carbon and polymer-based nanoparticles and alumina nanoparticles functionalized with vacuum residue have proved to be effective nano sorbents for oil-spill remediation (Franco, 2014) (Mehmood, 2021). Hydrophobic foam-like material made from melamine modified with furfuryl alcohol and lignin-based polyurethane/graphene oxide showed high efficiency for oil spill clean-up and recovery (Feng, 2017) (Oribayo, 2017).

Natural fibres are proven to be a good substitute for synthetic fibrous materials. Cotton fibres, kapok fibres and milkweed fibres are some natural fibres that (Karan, 2011) were tested. Raw luffa also showed good adsorption and had reusable efficiency of more than 50%. The biological treatment of oil spills involves using bacteria, fungi, and algae which has been discussed in (Abdelwahab, 2014).

ELECTROCOAGULATION

Electrocoagulation is an advanced technology that combines the concepts of coagulation, flotation and electrochemistry. It is proving to be an efficient technique for treating polluted water containing contaminants like heavy metals, oils and organic and inorganic compounds. The setup of an electrocoagulation system is very similar to that of an electrolytic cell where a set of electrodes connected to an electricity source is dipped in an electrolytic cell containing the water to be treated. The power source can either be DC or AC source but a higher efficiency has been seen in the case of using an AC source. The electrodes are generally made of aluminium or iron because they are easily available, reliable, and non-toxic in nature. Electrocoagulation, similar to chemical coagulation and chemical flotation, uses the concept of destabilization of the dissolved and suspended contaminants to make them charged and act like tiny magnets which get attached forming bigger agglomerates.

These larger flocs/agglomerates then settle down at the bottom of the container due to gravity. The anode acts as the coagulant supplier by dissociation. It produces metal ions like ferrous or ferric ions or aluminium ions which destabilizes the contaminants and very similar to the production of metal ions by chemical coagulants like ferrous sulfate or aluminium sulphate. The side reaction occurring in electrocoagulation is what makes it different from chemical coagulation or chemical flotation. The liberation of hydrogen bubbles along with hydroxide ions that leads to the increase of pH of the solution is an example of such a side reaction (reaction 6).

Three mechanisms involved in electrocoagulation are:

a. anode oxidation (in-situ coagulant formation)
b. gas bubble generation
c. flotation and sedimentation of flocs formed

The reaction involved in this process are listed from 1 to 5 are listed below,

$$Fe(s) \rightarrow Fe^{n+}(aq) + ne^{-1} \quad \ldots 1$$
$$4Fe^{2+}(aq) + 10H_2O + O_2(aq) \rightarrow 4Fe(OH)_3(s) + 8H^+ \quad \ldots 2$$
$$Fe^{2+}(aq) + 2OH^- \rightarrow Fe(OH)_2(s) \quad \ldots 3$$
$$Al(s) \rightarrow Al^{3+}(aq) + 3e^{-1} \quad \ldots 4$$
$$Al^{3+}(aq) + nH_2O \rightarrow Al(OH)_n^{3-n}(s) + nH^+ \quad \ldots 5$$
$$e^- + 2H_2O \rightarrow H_2 + 2OH^- \quad \ldots 6$$

Faraday's law is followed during the dissociation of the anode, which is given by,

$$m = \frac{ItM_w}{zF}$$

where I = current in ampere, t = time of operation in seconds, M_w = molecular weight in grams per mole, F = faraday's constant, z = number of electrons involved in the reaction and m = mass of the anode dissolved in grams.

Over the decade, extensive studies have been done on electrocoagulation, its applications and modifications to improve its functioning. It has been observed that factors like electrode material and its arrangements, type of power supply, current density and concentration of anions and pH of the solution are some factors that affect the functioning of electrocoagulation.

The electrodes may be monopolar or dipolar which are then arranged in series or parallel connections. The various arrangements have been shown in the figure. Out of the three monopolar parallel connections, electrodes have been seen to have the highest efficiency along with being the most cost-effective. Aluminium and iron are the most commonly used metals for electrodes. The iron may form a divalent or trivalent cation depending on the pH and potentially be applied across the electrodes. Aluminium always forms a trivalent cation.

One of the biggest problems faced is the cathode passivity due to the formation of an insoluble layer of hydroxide on the cathode which reduces the current flow between the electrodes and thus reduces the overall efficiency of the electrocoagulation system. This can be solved by switching the power source from DC to AC. (Moussa, 2017) states using an AC power supply led to lower energy consumption and higher pollutant removal efficiency.

In electrocoagulation, pH plays an important role because it affects electrode dissolution (it affects the formation of divalent or trivalent cation of iron), the zeta potential of the dissolved or suspended particles and the conductivity of the solution. As the pH of the solution is in constant change during the process hence is difficult to establish a relationship between the pH of the solution and the efficiency of the process (Moussa, 2017).

WATER TREATMENT USING ELECTROCOAGULATION

1) HEAVY METALS: electrocoagulation has been seen to remove heavy metals like arsenic, strontium, caesium, chromium, cadmium, zinc, nickel, mercury and cobalt (Akbal, 2010) (Al-Qodah, 2017). (Emamjomeh, 2009) conducted laboratory-scale experiments to remove arsenic using three different electrodes of iron, aluminium, and titanium. The highest removal efficiency of 99% was seen while using an iron electrode and at a pH range of 6-8. (Bazrafshan, 2015) (Emamjomeh, 2009) reported that 100% of cadmium was removed through an electro-flotation process with the aluminium electrode.
2) MICROPLASTICS: Electrocoagulation is a novel process that accompanies electrochemistry with the benefits of coagulation and flocculation (Xu, 2021). It is a cheap three-step process that doesn't involve any additional chemical reagent, generated relatively less amount of sludge, and is a cost and energy-efficient process.
As it does not use any additional chemical reagent except sacrificial electrodes, it does not lead to any secondary pollution which is seen in membrane technology and chemical treatment processes. The three consecutive stages include the separation of metal cations from anode under the action of an electric field to form micro-coagulant, their combination with the suspended particles and contaminants in water form colloidal floc which sinks at the bottom, and finally, the coagulant forms a layer of sludge and retains the once suspended contaminants.
The efficiency of the process can vary with the use of different electrodes, current intensity, pH, microplastic type, etc. The two most common electrodes are Al and Fe. (Shen M. Z., 2022) gave a comprehensive insight into the mechanism of electrocoagulation. It also reported that the Al electrode had a higher efficiency than the Fe electrode. The maximum removal of microplastics seemed at a pH of around 7.2 which is around 98% to 99% and the efficiency increased with an increase in applied voltage density till a certain value after efficiency becomes constant. According to Perren, 2018, the maximum removal of microbeads was observed at the lowest tested current density. Electrocoagulation has been to be more effective in removing microplastic fibres and hence can be used to treat wastewater from laundry (Akarsu, 2021) (Shen M. Z., 2022). The only drawback is the regular replacement of the sacrificial anode. It is still a new process under study to make it more effective. This also means it has yet to be tested at the pilot and commercial levels (Xu, 2021).
3) NITRATES AND PHOSPHATES: electrocoagulation can remove nitrates, phosphates, sulfides, sulfites, sulfates, fluorides, and nitrates.

(Ghazouani, 2020) reports a removal rate of 99% when the current density was increased from 1 mA/cm² to 40 mA/cm² at a natural pH using parallel mild steel electrodes. At a high current density, the reduction of nitrates to ammonia at the cathode was favoured over the adsorption process.

4) Electrocoagulation has also been reported to be effective in removing pollutants from the tannery, dyes, organic wastes from the paper industry and sewage, persistent organic compounds and can adsorb emulsified oil and other aromatic compounds from water (Emamjomeh, 2009).

BENEFITS OF ELECTROCOAGULATION

It is a relatively simple and eco-friendly technique where sludge production is very less and is generally non-toxic in nature. No additional chemical is required in this process and the treated water is clear, colourless and odourless. It can remove the dissolved heavy metal ions as well as suspended particulate pollutants from water. The generation of H_2 gas helps in this process through the process of flotation bringing the lighter pollutants to the surface which can be easily skimmed off (Emamjomeh, 2009) (Moussa, 2017).

PROBLEMS FACED IN ELECTROCOAGULATION

Electrocoagulation has proved to be very efficient in removing pollutants from water at a laboratory scale level but its efficiency at the industry level is yet to be tested. One of the biggest problems faced in this process is the availability of large-scale electrodes for its periodic replenishment after it is completely dissociated which makes it an expensive process. Cathode passivation is another problem faced in this process. This can be solved by including additional additives or using an AC source. Adding additives might lead to the production of secondary pollutants which may also be toxic (Emamjomeh, 2009) (Moussa, 2017).

CONCLUSION

Through this literature review work, two emerging pollutants microplastics and heavy metal contaminants, their sources, hazards and some of the conventional methods of their removal like waste-water treatment plants, membrane technologies, coagulation and flocculation have been discussed. Adsorption using novel organic and inorganic adsorbents, electrocoagulation and other new methods are also working for it. It can be concluded that:

- Accurate, precise and cheap assessment techniques for the detection of emerging pollutants are required
- Translation of the lab-scale removal methods to large industry-scale process is needed
- The process should be flexible and adaptive to remove new environmental pollutants
- None of the processes is effective in itself and needs the assistance of some other method also.

Analysing the above mentioned points, we can deduce that today's situation of nano/micro plastic pollution calls for an efficient, reproducible, economic technology which is stable enough to give high output both as an incorporated and a standalone procedure. ♦

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