EFFECT OF TOXIC HEAVY METALS ON ECOSYSTEM

Abstract

Surface water has been utilized for a wide range of purposes by humans. It serves as a source of drinking water after undergoing treatment, and it's also used as a source of untreated domestic water, particularly in rural areas of developing countries. Farmers rely on it for irrigation, while fishermen make their living by harvesting fish from numerous freshwater sources. Additionally, it is used for recreational activities like swimming and serves as attractions for tourists. It is essential to take measures to safeguard surface water from pollution.

In many developing countries worldwide, a significant portion of the population still relies on untreated surface water as their primary source of household water. This is primarily due to the lack of access to treated drinking water or insufficient water delivery systems, a problem that is particularly acute in rural regions. The issue is further exacerbated in these rural areas. The increasing population and industrialization are putting undue stress on surface water resources.

In aquatic and soil ecosystems, various forms of trace metals exist, both soluble and particulate, which can influence their impact on these biological systems. To accurately determine the low concentrations of these metals, it is essential to employ proper techniques for inspection and investigation. Although many regulatory programs assess metals based on data related to their total concentrations, such values often do not directly correlate with their environmental impacts. Consequently, alternative approaches are needed to predict potential risks effectively.

Keywords: heavy metals, toxic metals, pollution, GAC, activated carbon, lead.

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I. INTRODUCTION

Pesticides, fertilizers, paper production, and metal mining are among the rapidly growing industries that have consistently released various pollutants into the aquatic ecosystem through wastewater discharge. These pollutants, even at extremely low concentrations, pose a significant threat to aquatic organisms due to their high content of organic and inorganic chemicals, as well as toxic heavy metals such as nickel (Ni), cobalt (Co), aluminium (Al), lead (Pb), chromium (Cr), cadmium (Cd), mercury (Hg), and zinc (Zn). Notably, these metals are sourced from activities like metal electroplating, mining, battery manufacturing, petroleum refining, and paint production, especially in developing countries. In addition to industrial sources, agricultural, domestic, and sewage waste are also negligently released into water bodies. Nevertheless, water pollution caused by heavy metals is more pronounced than other forms of pollution, particularly when these metals are introduced into the natural environment.

II. EFFECT OF TOXIC METALS ON ECOSYSTEM

Water, the fundamental source of life on Earth, plays an indispensable role in sustaining our planet's ecosystems and all living organisms. This vital resource is in constant motion through the intricate and dynamic system known as the water cycle. The water cycle orchestrates the perpetual movement of water between the Earth's vast oceans and its diverse landscapes. Despite the dynamic nature of water, the total amount of water on, in, or above our planet remains finite, maintaining a delicate balance. This means that Earth's water resources are not increasing or decreasing; they are simply redistributed within the system.

Freshwater, a subset of Earth's water resources, holds paramount importance for both human civilization and the biodiversity that thrives in our ecosystems, encompassing a wide array of flora and fauna. However, freshwater is a finite and fragile resource, necessitating judicious management to ensure its sustainability. The sources of freshwater are diverse and encompass wetlands, lakes, rivers, streams, and underground aquifers. These natural reservoirs perform a dual role in our ecosystem. They not only store freshwater but also act as natural filters, purifying this invaluable resource. Their significance lies in their role as a lifeline for both human populations and the myriad of species that rely on freshwater for survival.

Healthy freshwater sources are multifaceted and serve various crucial functions in our society. They supply the water needed for agriculture, drinking, industrial processes, energy production, and transportation. Furthermore, they play an instrumental role in mitigating environmental challenges, such as erosion control, waste disposal, and natural flood protection. Regrettably, human actions have not consistently reflected a responsible stewardship of this precious resource. Freshwater sources have been mismanaged, leading to a plethora of issues, including pollution, the depletion of watercourses, and harm to ecosystems. In recent decades, we have witnessed the loss of a substantial number of wetlands worldwide, along with the biodiversity they support. The consequences of contaminated water have reverberated through society, resulting in serious health concerns and significant economic costs.

Wetlands, in particular, are highly susceptible to eutrophication, a phenomenon where excessive nutrients are introduced into the ecosystem, often present in both low and high concentrations due to the unique organic composition of these water bodies. Additionally, heavy metals tend to accumulate at the base of wetlands, near their central points. The overall potential ecological risk index is on the rise, primarily driven by cadmium (Cd) and mercury (Hg), which are the dominant contributors to heavy metal contamination. Consequently, there is an urgent need to prevent and remediate contaminated residues to avert secondary pollution. The dispersion of both organic compounds and heavy metals is strongly influenced by natural conditions.

Water pollution involving hazardous metals raises significant concerns for both human health and environmental well-being. The discharge of heavy metals into water resources constitutes a grave issue, and the resulting pollution can impair the quality of water supplies. Industrial wastewater from diverse sectors contains heavy metals, including copper, zinc, cadmium, lead, nickel, chromium, and others, which have the potential to inflict substantial harm on the environment. The increasing concentrations of these metals in water sources pose a significant health risk, owing to their persistence and toxicity.

Pollution, the introduction of undesirable substances into the environment through direct or indirect human activities, is a pressing global challenge. Substances responsible for pollution, known as pollutants, can encompass a wide range of agents, including chemical, physical, or organic compounds, released into the environment. These pollutants have detrimental effects on both human populations and other living organisms, jeopardizing the integrity of ecosystems.

The rapid expansion of various industries, such as metal mining operations, fertilizer production, paper manufacturing, and pesticide use, has consistently led to the release of diverse pollutants into aquatic ecosystems via wastewater discharge. These pollutants pose a significant risk to aquatic organisms, even at extremely low concentrations, due to their diverse chemical composition. This composition includes organic and inorganic substances, coloured materials, and toxic heavy metals like zinc (Zn), nickel (Ni), cobalt (Co), chromium (Cr), aluminium (Al), cadmium (Cd), lead (Pb), and mercury (Hg). Many of these metals originate from industrial activities such as metal electroplating, mining, battery manufacturing, petroleum refining, and paint production, particularly in developing nations. Additionally, agricultural, domestic, and sewage wastes continuously find their way into water bodies. However, water pollution caused by heavy metals stands out as particularly severe when these contaminants are introduced into the environment.

Most heavy metal elements are highly toxic when their concentration exceeds permissible limits within ecosystems. Elevated levels of heavy metals can accumulate within the human body through water and the food chain, resulting in severe health issues when these metals exceed safe thresholds. These non-biodegradable metals tend to accumulate within the food chain and exhibit high toxicity, with many of them being carcinogenic. Their detrimental effects have far-reaching consequences, profoundly impacting our ecosystem, human health, and the broader environment. Addressing these challenges requires concerted efforts in pollution prevention, remediation, and sustainable water resource management.

III. POLLUTION AND THEIR TYPES

Water pollution is a global concern in the contemporary world, as water is an essential component of life and vital to the well-being of all living organisms. Water, in its various forms, serves as a basic necessity for not only humans but also countless other species on Earth. When undesirable substances are introduced into any part of the environment, primarily due to human activities involving the discharge of by-products, waste materials, or harmful secondary products, it leads to a condition referred to as pollution.

Within the broader realm of pollution, various types of pollution can be identified, each with its own unique characteristics and impact on the ecosystem. These include:

1. **Air Pollution:** Air pollution pertains to the presence of hazardous substances in the air, occurring in solid, liquid, or gaseous forms, along with the presence of excessive noise and radioactive radiation. These substances reach levels within the ecosystem that can prove detrimental to human beings and other living organisms. The primary causes of air pollution are the escalating use of fossil fuels in power plants, industries, transportation, mining, and residential construction. Air pollutants are categorized into two main types: solid suspended particles and gaseous pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and others.

   According to the World Health Organization (WHO), air pollution is defined as the contamination of both indoor and outdoor environments by any chemical, physical, or biological agent that alters the natural characteristics of the atmosphere. These alterations arise primarily from human activities such as manufacturing, energy production, and the disposal of waste materials into the surrounding environment, all of which can impact plant metabolism.

   Air pollutants can further be classified into two categories:

   - Primary pollutants, which originate directly from the source and immediately contaminate the ecosystem. Examples include sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and various pesticides.
   - Secondary pollutants, which arise from primary pollutants through chemical reactions. Notable air pollutants include SO_2 and black smoke, which are conventional pollutants resulting from the use of coal and oil for domestic purposes and power generation. Lead is released into the air in the form of fumes or dust through activities like burning petrol, steel production, and coal combustion. Carbon dioxide is generated through the incomplete combustion of carbon-based fuels.

2. **Radiation Pollution:** Radiation pollution encompasses the physical pollution of living organisms and their environment due to the release of radioactive substances into the environment. This release occurs during nuclear explosions, nuclear weapon testing, nuclear weapons manufacturing and decommissioning, mining of radioactive ores, handling and disposal of radioactive waste, and incidents at nuclear power plants. Nuclear tests are conducted to assess the effectiveness, yield, and explosive capabilities of nuclear weapons, with radioactive pollutants accounting for 15% of the total energy released in such explosions. Radioactive pollution extends to water bodies, water resources, and

airspace, resulting from the radioactive fallout generated by nuclear explosions. Radionuclides are the primary sources of this pollution, emitting beta particles and gamma rays as radioactive substances decay.

3. **Soil Pollution:** Soil pollution, often referred to as soil contamination, involves the introduction of materials that adversely affect the quality or fertility of the soil. Water pollution can also contribute to soil pollution. Solid waste, including a mixture of plastics, clothing, glass, metal, organic matter, sewage, sewage sludge, and construction debris generated from residential, industrial, and commercial activities, is a significant source of soil pollution. Other contributors include fly ash, iron and steel slag, medical and industrial waste disposed of on land, fertilizers, and pesticides used in agriculture that reach the soil through runoff, and municipal waste deposited on landfills. Soil pollution can also result from acid rain and the dry deposition of pollutants on land.

   In essence, soil pollution represents the degradation of soil quality due to the excessive presence of chemicals, high concentrations of unwanted foreign substances, and the depletion of essential soil minerals and nutrients, often resulting from rapid soil erosion. This degradation arises from practices such as intensive cultivation of crops, the use of pesticides, and the application of chemical fertilizers.

   In conclusion, pollution in its various forms has a profound impact on the environment and the well-being of all living organisms, including humans. Addressing these pollution challenges requires a multi-pronged approach that includes pollution prevention, remediation efforts, and sustainable practices to safeguard our planet's ecosystems and ensure a healthier future for all.

4. **Marine Pollution:** Marine pollution, particularly from domestic sewage in coastal areas, stands as a significant environmental challenge. Annually, approximately 4.4 cubic kilometres of such waste are discharged into the Indian Ocean. Additionally, industrial waste, totalling around 0.44 cubic kilometres, including materials from paper, chemicals, pharmaceuticals, plastics, leather, food processing, jute, pesticides, oils, and heavy metals like lead, zinc, cadmium, and mercury, are released into the seas surrounding India. Some of these substances, when discharged into rivers, can pose critical problems for marine waters. Pesticides, for instance, are believed to have transferred up to 25 percent of the dichlorodiphenyltrichloroethane (DDT) used to the sea. The impact of DDT and pesticide compounds on marine life is substantial, resulting in reproductive failures in fish and the inhibition of photosynthetic processes.

5. **Noise Pollution:** Noise pollution is characterized by "unnecessary sound with no value" or any sound that is unwelcome to its recipient. Industries such as stone cutting and crushing, metal forging, loudspeakers, hawkers' shouting, the movement of heavy vehicles, railway operations, and airport activities generate excessive noise that can lead to irritation, elevated blood pressure, mood disturbances, decreased work efficiency, and, in some cases, hearing loss, which, though initially temporary, can become permanent if exposed to prolonged noise pressure. Therefore, effective noise control is of utmost importance. Noise levels are measured in decibels (dB), with the World Health Organization (WHO) recommending a maximum noise level of 45 dB during the day and 35 dB at night. Noise levels exceeding 80 dB are considered hazardous.

6. **Thermal Pollution:** Thermal pollution arises primarily from the activities of power plants, both thermal and nuclear, as well as various chemical and industrial operations. These facilities use substantial amounts of water for cooling purposes, and the heated water is subsequently discharged into rivers, streams, or oceans. The waste heat generated by boilers and heating processes elevates the temperature of the cooling water. The discharge of hot water can raise the temperature of the receiving water by 10 to 15°C above the ambient water temperature, a phenomenon known as thermal pollution. Increased water temperature leads to a decrease in dissolved oxygen in the water, which adversely impacts aquatic life. Unlike terrestrial ecosystems, water bodies typically maintain a stable temperature, and any fluctuations can significantly affect aquatic plants and animals. Therefore, the discharge of hot water from power plants can have detrimental effects on aquatic ecosystems, especially in warm tropical waters where aquatic organisms are already operating near the upper limits of their temperature tolerance.

7. **Water Pollution:** The importance of a safe and clean water supply cannot be overstated, as it is a fundamental necessity for living organisms, particularly for drinking purposes. Surface water, found in various forms such as rivers, lakes, and ponds, has been utilized for numerous purposes by humans. It serves as a source of potable water after treatment and, in some cases, as a source of untreated domestic water, especially in rural areas of developing countries. Surface water is also used for irrigation by farmers, and it provides a livelihood for fishermen who harvest fish from these freshwater sources. Additionally, it serves as a venue for recreational activities and tourist attractions.

   Surface water, however, requires diligent protection from pollution to maintain its suitability for these purposes. The primary sources of freshwater pollution are raw and partially treated wastewater. The discharge of domestic and industrial wastewater has contributed to the escalation of freshwater pollution and the depletion of clean water resources. In many developing countries, a significant portion of wastewater generated does not undergo any form of treatment. While some urban centers may have various wastewater treatment facilities (WWTFs), many of them produce inadequately treated effluents, which are subsequently discharged into freshwater bodies. In contrast, developed countries have established adequate supplies of potable water and improved sanitation facilities, enforced strict environmental regulations, and implemented monitoring measures to prevent undue pollution of freshwater resources. These efforts have resulted in fewer instances of waterborne diseases compared to developing countries.

   However, in developing countries, a significant portion of the population still relies on untreated surface water as their primary source of domestic water supply. This is primarily due to the lack of consistent access to potable water and insufficient water delivery systems, particularly in rural areas. Surface water resources in such regions are facing increased stress due to population growth and intensified industrialization. The accessibility of surface water makes it a preferred option for wastewater discharge, even though this practice leads to irreversible harm to aquatic ecosystems and poses risks to human health. Pollutants present in wastewater, including various microorganisms, heavy metals, radionuclides, pharmaceuticals, and personal care products, compromise the aesthetic value of water, reduce the availability of usable water, increase the cost of purification, contaminate aquatic resources, and affect food supplies. Pollution, combined with the high demand for water, negatively impacts biodiversity, ecosystem function, and the natural services provided by aquatic systems that society relies upon.

Urban areas in many developing countries may have wastewater management systems, some of which are effective and meet international standards, while others suffer from poor design, maintenance issues, and expansion challenges due to insufficient investment. In contrast, most rural and impoverished communities lack any form of wastewater management systems. Effluents from both large- and small-scale industries are often discharged into surface water bodies, resulting in pollution, loss of biodiversity in aquatic ecosystems, and potential health risks to the human population.

The presence of harmful contaminants in water bodies, such as ponds, lakes, and rivers, affects the well-being of communities that depend on these water sources for their daily needs, including water supply, fisheries, and agriculture. The accumulation of metals in water bodies can lead to the buildup of these substances in human kidneys, livers, and bones, disrupting metabolic activities and potentially causing cardiovascular, neurological, and renal diseases. Water pollution, therefore, represents a critical issue that requires comprehensive strategies to safeguard both the environment and human health. [1,2]

Table 1: Major Sources and Toxic Effect of Various Heavy Metals on Ecosystem.

Metal pollutant	Major Source	Toxic effect to ecosystem
Copper	Electronics plating, paint manufacturing, wire drawing, copper polishing, and printing operations	Dizziness, diarrhoea, normocytic, hypochromic anaemia, leukopenia, and osteoporosis Reproductive and developmental toxicity, neurotoxicity, and acute toxicity.
Nickel	Electroplating, non-ferrous metal, mineral processing, copper sulphate manufacturing.	Reduced lung function, lung cancer,chronic bronchitis, dermatitis, chronic asthma.
Zinc	Mining and manufacturing processes	metal-fume fever for short term, gastrointestinal distress,nausea and diarrhoea.
Lead	Manufacturing of batteries, pigments, electroplating, ammunition	Spontaneous abortion, brain damage, anorexia,malaise, anaemia, loss of appetite, nervous system damage.
Mercury	Volcanic eruptions, forest fires, battery	Corrosive to skin, eyes, muscles, neurological and renal disturbances,
Arsenic	Smelting, mining, energy production from fossil fuels, rock sediment's, Metal processing plants, burning of fossil fuels, mining of arsenic containing ores and use of arsenical pesticides	Bone marrow depression, hemolysis, liver tumors, gastrointestinal symptoms, cardiovascular and nervous system functions disturbances, Internal cancer, skin lesions and death

Cadmium	Electroplating, smelting, alloy manufacturing, pigments, plastic and mining	Itai–Itai disease, carcinogenic, renal disturbances, lung insufficiency, bonelesions, cancers, hypertension, weight loss, liver and kidney damage
Chromium	Electroplating, paints and pigments, metal processing, steel fabrication and canning industry	Epigastric pain, nausea, vomiting, severe diarrhea, lung tumors, Carcinogenic, mutagenic, teratogenic, Normocytic, hypochromic anemia, leukopenia, and osteoporosis; copper deficiency

Trace metals found in aquatic and soil environments exist in a variety of soluble and particulate forms, each of which can have distinct effects on biological systems within these ecosystems. To accurately assess and investigate low metal concentrations, it is imperative to employ proper techniques and methodologies.

Traditionally, many regulatory programs have relied on data related to the absolute metal concentrations in the environment as a basis for assessment. However, it has become evident that such measurements often do not directly correlate with the actual impacts of these metals on ecosystems. Consequently, alternative approaches are necessary to better predict the potential risks associated with metal contamination.

One critical factor influencing the bioavailability of metals is their speciation. This concept was initially established for copper in aquatic systems, where the toxicity of metals is primarily linked to the presence of free metal ions. The interaction between metals and naturally occurring organic matter can also significantly affect their bioavailability. Small concentrations of organic matter can strongly complex with metals, potentially enhancing their toxicity.

Table 1.1 provides an overview of major sources and the toxic effects associated with various heavy metals on our ecosystem. This information underscores the importance of understanding the speciation and bioavailability of these metals to accurately assess their ecological impact.

In summary, the assessment of trace metals in aquatic and soil environments is a complex task that requires a nuanced understanding of their speciation and bioavailability. Relying solely on absolute metal concentrations may not provide an accurate representation of their potential harm to ecosystems. As such, ongoing research and innovative techniques are necessary to enhance our ability to predict and mitigate the environmental risks associated with heavy metal contamination. [3,4].

Drinking water has gained recognition as a significant source of human exposure to arsenic, with both organic and highly toxic inorganic forms present. Arsenic, behaving as a metalloid, is naturally found in various environmental compartments, including food, soil, air, and water. In food, both organic and inorganic arsenic species coexist, while drinking water primarily contains inorganic forms of arsenic. Among these, As(III) species are particularly mobile in groundwater and are 60 times more toxic than As(V).

The presence of arsenic in the environment can be attributed to both natural and human-related factors. Natural processes, such as coal-fired power plants, burning vegetation, and volcanic activity, contribute to about one-third of the arsenic in the atmosphere. The remaining two-thirds arise from human activities. Deep-drilled wells can be especially vulnerable to natural geological contamination, resulting in high levels of inorganic arsenic in drinking water.

Arsenic exposure is associated with a range of health issues, including skin and internal cancers, cardiovascular disease, impacts on the mental development of children, and neurological effects. To safeguard public health, the World Health Organization (WHO) recommends that the concentration of arsenic in drinking water should not exceed 10 µg/L [5].

Cadmium and its compounds are widely used in various industries, posing a significant danger due to their extreme toxicity even at relatively low doses. Exposure to cadmium can result in kidney damage, renal disorders, high blood pressure, bone fractures, the destruction of red blood cells, heart disease, cancer, and diabetes. Cadmium tends to accumulate in the kidney, liver, and other organs, making it more toxic than lead or mercury [6].

Chromium exists in two oxidation states, Cr(III) and Cr(VI), each with varying levels of toxicity, mobility, and bioavailability. While Cr(III) is essential for human nutrition, relatively harmless, and stable, Cr(VI) compounds are highly toxic and can lead to lung cell damage. Chromium is extensively used in industries such as leather tanning, cement production, dyeing, metallurgy, wood treatment, paint manufacturing, textiles, steel production, and canning. The permissible concentration limits for chromium in inland surface waters and drinking water are set at 0.1 mg/L and 0.05 mg/L, respectively. [7]. Prolonged inhalation of Chromium (VI) exacerbates the risk of lung, nasal, and sinus cancer and can cause severe dermatitis and skin ulcers [8,9].

Copper is commonly found in effluents from a range of industries, including brass manufacturing, petroleum refining, boilers, plumbing, textile production, marine painting, electroplating, mining, and various agrochemical sectors [10].

Antimony is a toxic substance of significant concern in water supplies intended for drinking. Regulatory bodies such as the US EPA and EU have established very low maximum permissible contaminant levels for antimony in drinking water. High concentrations of antimony are associated with the production of flame retardants, batteries, chemicals, ceramics, and certain mining operations. Antimony can exist in two oxidation states, Sb(III) and Sb(V), in water, with Sb(III) generally considered more toxic, especially in less oxygenated systems [11].

Zinc, while essential in trace amounts, can become toxic at higher concentrations due to the discharge of wastewater from various industries such as galvanizing, metallurgy, electroplating, mining, paints and pigments, pharmaceuticals, fiber production, groundwood pulp, newsprint paper production, battery manufacturing, petroleum refining, and petrochemical processing. Zinc, being non-degradable, can enter the food chain and accumulate in living organisms, leading to various diseases. The permissible concentration of zinc in drinking water, according to WHO standards, is 5 mg/L [12].

Nickel occurs naturally in the environment, including soil, sea salts, volcanic ash, and as particles in smoke from forest fires. It exists in various forms, such as sulphides, arsenides, antimonides, and oxides, with Ni(II) being more toxic and carcinogenic than Ni(IV). Industrial processes, including leather tanning, electroplating, wood preservation, and steel manufacturing, release nickel into the environment. Prolonged exposure to higher concentrations of nickel can result in lung, nose, and bone cancers, as well as various health issues like headaches, dizziness, nausea, vomiting, chest pain, and weakness [13].

Cobalt, an essential trace element, plays vital roles in various organisms. However, it is released into the environment through industrial activities such as mining, electroplating, painting, metallurgy, pigment production, and the manufacturing of lithium-ion batteries. Such discharges can have serious health effects on animals and humans, including contact dermatitis, paralysis, lung irritation, and bone defects. Additionally, exposure to ionizing radiation is associated with an increased risk of developing cancer. The permissible limits for cobalt in irrigation water and livestock wastewater are set at 0.05 mg/L and 1 mg/L, respectively [14].

Table 2: USEPA set Maximum Contaminated Level (MCL) standards, for toxic metals [15].

Water Pollutant	Toxic effect	MCL (mg/L)
Arsenic	Skin manifestations, visceral cancers, vascular disease	0.05
Cadmium	Kidney damage, renal disorder, human carcinogen	0.01
Chromium	Headache, diarrhea, nausea, vomiting, carcinogenic	0.05
Copper	Liver damage, Wilson disease, insomnia	0.25
Nickel	Dermatitis, nausea, chronic asthma, coughing, human carcinogen	0.20
Mercury	Rheumatoid arthritis, and diseases of the kidneys, circulatory system, and nervous system	0.00003
Zinc	Depression, lethargy, neurological signs and increased thirst	0.80
Lead	Damage the fetal brain, diseases of the kidneys, circulatory system, and nervous system	0.006

Lead is a metallic element that falls within the group IV elements and occupies the sixth period of the periodic table. This bluish-grey metal occurs naturally and is typically found in conjunction with sulfur or oxygen minerals. Due to its various advantageous properties, lead finds extensive applications across multiple industries, including storage-battery manufacturing, printing, pigment production, petrochemicals, fuel combustion, and the creation of photographic materials.

However, it is crucial to acknowledge that lead is a highly toxic substance with the capacity to accumulate within living organisms. Exposure to lead can lead to severe health consequences, encompassing cognitive impairments, behavioral disturbances, kidney damage, anemia, and toxicity affecting both the reproductive and nervous systems. It is essential to note that governmental guidelines, such as the Indian Standard IS: 10500, have established a permissible limit for lead concentration in drinking water, which is set at a maximum of 0.01 milligrams per liter (mg/L).

In summary, lead, while widely employed in various industrial applications, poses significant health risks due to its toxic nature and potential for bioaccumulation in living organisms. Therefore, strict regulatory standards, such as the IS: 10500 guidelines, aim to safeguard public health by limiting lead exposure through drinking water. [16].

In the intricate processes of haemoglobin synthesis and porphyrin metabolism, lead forms metal complexes by binding with oxo-groups within enzymes, thus exerting a direct influence on their enzymatic activity [17]. The introduction of lead ions into the body can occur through multiple routes, including inhalation, ingestion, or absorption through the skin. Consequently, when the human body is exposed to lead, it manifests itself as a cumulative poison, with lead primarily accumulating in vital organs such as bones, kidneys, the brain, and muscle tissues.

This accumulation of lead can give rise to a spectrum of severe health disorders, encompassing kidney disease, anemia, nervous system disorders, and, in extreme cases, even fatalities. One particularly concerning aspect of lead exposure is its propensity to substitute for calcium, an essential mineral crucial for maintaining strong bones and teeth, as well as for facilitating the normal functioning of the nervous system, including sympathetic actions on nerves and blood vessels.

Furthermore, the presence of elevated lead concentrations in the body can have profound developmental consequences, especially in children, where it can impair cognitive development. Additionally, lead's interference with enzymatic processes within the body, such as replacing essential elements like zinc in heme enzymes, underscores its role as an enzyme inhibitor, further exacerbating its adverse effects on human health [18].

Exposure to lead (Pb) can occur through various pathways, including the inhalation of contaminated dust particles and aerosols or the ingestion of food and water that has been contaminated with lead. The deleterious effects of lead poisoning in humans are extensive, affecting multiple organ systems including the kidneys, liver, heart, brain, skeletal system, and the nervous system. The initial symptoms of lead poisoning due to exposure often include headaches, a sense of dullness, memory loss, and irritability [18].

One of the significant consequences of lead exposure is its impact on the synthesis of hemoglobin, which can lead to anemia. In children, chronic exposure to low levels of lead can have particularly detrimental effects, potentially diminishing their intellectual capacity. It's worth noting that the International Agency for Research on Cancer (IARC) has classified lead as a possible carcinogenic substance in humans, further underlining its health risks.

Regulatory bodies have established limits to mitigate lead exposure. According to the U.S. Environmental Protection Agency (EPA), the allowable limit of lead in drinking water is set at 15 parts per billion (ppb). Additionally, the World Health Organization (WHO) has recommended safe limits for lead in wastewater and soils used for agriculture, which are 0.01 parts per million (ppm) and 0.1 ppm, respectively. These guidelines are essential for safeguarding public health and minimizing the adverse effects of lead exposure on both individuals and the environment.

Lead is frequently found as a prominent heavy metal contaminant in wastewater that is often released into natural water bodies without undergoing appropriate effluent treatment prior to disposal. In its natural state, lead exists as a stable metal within the Earth's crust. It possesses notable physical properties, including a high density of 11.34 g/cm^3, a melting point of 327°C, and a boiling point of 1755°C.

Lead's chemical characteristics are also noteworthy. It demonstrates solubility in nitric acid and hot concentrated sulfuric acid, which makes it susceptible to dissolution under certain acidic conditions. However, it is important to note that lead is generally insoluble in water at a standard temperature of 25°C and typically does not dissolve in organic solvents. This limited solubility in water is a significant factor in its tendency to accumulate in aquatic ecosystems and poses risks to both environmental and human health.

When untreated wastewater containing lead is released into aquatic ecosystems, it sets in motion a chain of adverse effects that have far-reaching consequences. Chief among these is the contamination of the aquatic environment, which can have detrimental impacts on the delicate balance of aquatic ecosystems.

Lead, being a heavy metal, has a tendency to persist in water bodies, and this persistence can lead to bioaccumulation. Bioaccumulation occurs when lead accumulates in the tissues of aquatic organisms over time as they ingest contaminated water or prey. This process can lead to elevated levels of lead within the food chain, ultimately affecting not only aquatic life but also organisms higher up in the food web, including humans who consume contaminated aquatic species.

To address this critical issue, it is imperative to emphasize the importance of effective wastewater management and treatment protocols. Properly treating wastewater to remove or significantly reduce lead concentrations before discharge is a key strategy in mitigating the adverse impacts on ecosystems. By doing so, we can help safeguard the health of aquatic environments, protect biodiversity, and ensure the safety of water resources for various uses, including drinking water, agriculture, and recreation.

Essentially, the responsible management and treatment of wastewater containing lead are of paramount importance, not only for the preservation of our ecosystems but also for the well-being of communities that rely on these invaluable water resources. This proactive approach plays a pivotal role in preventing further contamination and maintaining a sustainable, harmonious balance within our aquatic ecosystems [19].

Lead is a metal known for its unique properties, including a low melting point and corrosion resistance, making it a common choice in plumbing systems. Unfortunately, lead is persistent in various environmental mediums such as water, air, and soil, primarily due to its presence in a wide range of manufactured products. These products encompass solders, paints, ceramics, water pipes, leaded gasoline, and even shielding materials used in X-ray machines. The demand for lead continues to rise annually, especially driven by the expanding industrial sector. Notably, the battery industry accounts for a substantial portion of global lead consumption, with more than two-thirds of lead used in the production of car batteries. China stands out as a significant contributor to lead production, particularly for lead-based batteries, and is expected to further drive the demand for lead manufacturing [20].

Interestingly, there is potential for utilizing natural materials abundant in supply or certain agricultural waste products as cost-effective adsorbents for lead removal. These materials represent untapped resources that are widely available and environmentally friendly, making them promising candidates for addressing lead pollution challenges [21].

One particularly effective and economically viable technology for lead removal is biosorption. This method leverages various biological materials such as cellulose, hemicelluloses, and lignin, each with distinct metal-binding capacities. These materials serve as efficient adsorbents for pollutant removal due to the presence of functional groups like carboxyl, hydroxyl, methoxyl, and phenols, which enable them to effectively bind and remove lead from contaminated environments [22].

In summary, responsible wastewater management, awareness of lead's pervasive presence in various products, the use of natural materials as adsorbents, and the application of biosorption technologies are all crucial components of a comprehensive strategy to mitigate lead contamination, protect our ecosystems, and ensure the well-being of communities that rely on clean and safe water sources.

IV. GRANULAR ACTIVATED CARBONS

Activated carbon is widely recognized and extensively utilized for the removal and recovery of hazardous metals from various sources, primarily due to its abundant availability and its remarkable affinity for scavenging metal ions. Granular Activated Carbon (GAC) offers several distinct advantages when it comes to adsorption processes, making it a valuable tool in environmental remediation:

1. **Large Adsorption Capacity**: GAC boasts a substantial capacity for adsorbing pollutants and organic molecules. This attribute arises from its unique porous structure, which provides an expansive surface area for interaction with contaminants.

2. **Versatile Adsorption:** GAC exhibits the ability to adsorb and retain a diverse range of chemicals simultaneously. This versatility is crucial in wastewater treatment scenarios where multiple contaminants may be present.

3. **Ozone Catalysis:** Another notable feature of GAC is its remarkable capacity for catalytically destroying ozone, a major component of smog. This property contributes to the mitigation of air pollution, further underscoring its environmental significance.

4. **Temperature and Humidity Robustness:** GAC performs effectively across a broad spectrum of temperature and humidity conditions, rendering it adaptable for use in various environmental settings and climates.

5. **Odour and Chemical Removal:** GAC demonstrates a preference for adsorbing odors and chemicals over moisture, making it particularly valuable in applications where the removal of specific odor-causing compounds is necessary.

6. **Safety and Inertness**: GAC is known for its inert nature, rendering it safe to handle and use in diverse industrial and environmental contexts.

Activated carbon is essentially a microcrystalline, porous, and non-graphitic form of carbon that has undergone processing to enhance its internal porosity. Its specific surface area typically ranges from 500 to 2500 square meters per gram (m^2/g). This surface area parameter is a critical physical property of activated carbon because it substantially enhances the physical adsorption of gases and dissolved substances from various media.

In wastewater treatment, activated carbons, and particularly GAC, have proven to be highly effective adsorbents for a wide array of contaminants. Their versatility, large adsorption capacity, and environmental compatibility make them invaluable tools for mitigating water pollution and safeguarding the quality of water resources. As environmental challenges persist, the continued exploration and application of activated carbon-based solutions hold great promise for addressing emerging pollution concerns [23].

The production of activated carbon involves two fundamental processes: physical activation and chemical activation, each with its distinct characteristics and applications. It's important to note that these processes offer various benefits depending on the intended use of the activated carbon.

- **Physical Activation:** In the physical activation process, carbonization and activation are carried out as separate steps. This method typically involves exposing the raw material to high temperatures. Compared to chemical activation, physical activation occurs at higher temperatures.

- **Chemical Activation:** In contrast, chemical activation combines both carbonization and activation simultaneously. During this process, the raw material is impregnated with specific inorganic salts. Subsequently, the soaked material is carbonized at relatively lower temperatures. Afterward, the resulting activated char is subjected to a thorough washing process using acid and water. Activated carbons produced through chemical activation are commonly used in liquid-phase purification systems.

Types of Activated Carbon Based on Physical Characteristics: Activated carbons can be classified into various types based on their physical characteristics, each designed for specific applications. These include:

- **Powdered Activated Carbon (PAC):** Fine particles of activated carbon, suitable for use in water treatment and gas-phase applications.

- **Granulated Activated Carbon (GAC):** Larger granules of activated carbon, often used in water treatment, air purification, and gas-phase adsorption.
- **Extracted Activated Carbon (EAC):** Activated carbon specifically designed for the extraction of specific compounds or contaminants.
- **Impregnated Carbon:** Activated carbon treated with additional chemicals to enhance its adsorption capabilities for particular substances.
- Polymer Coated Carbon: Activated carbon coated with polymers, enhancing its affinity for specific contaminants or improving its performance in certain applications.
- **Coconut Shell-Based Activated Carbon:** Coconut shells can be used as a source of fuel and charcoal. Notably, activated carbon derived from coconut shells is considered superior to other sources due to its unique characteristics. This superiority is attributed primarily to its small macrospore structure, which enhances its effectiveness in adsorbing gases, vapours, and removing impurities, colour, oxidants, and odours from various compounds.

In summary, the choice between physical and chemical activation processes depends on the desired properties and applications of the activated carbon. Activated carbon plays a critical role in various industries, ranging from water treatment to gas purification, and its effectiveness is often influenced by the production process and the source material used. Coconut shell-based activated carbon, with its specific advantages, stands out as a highly efficient and versatile option for numerous purification and adsorption applications [24].

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