sustainability

MDPI

Review

Removal of Inorganic Pollutants from Wastewater: Innovative Technologies and Toxicity Assessment

Vinay Kumar [1,*], Munish Sharma [2], Sonica Sondhi [3], Komalpreet Kaur [4], Deepak Sharma [3], Shivali Sharma [5] and Divya Utreja [5]

[1] Bioconversion and Tissue Engineering Laboratory, Department of Community Medicine, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences (SIMATS), Thandalam 602105, India
[2] School of Life Sciences, Central University of Himachal Pradesh, Shahpur Campus, Kangra 176206, India; munishptc@gmail.com
[3] Department of Biotechnology, Chandigarh College of Technology, Chandigarh Group of Colleges Landran, Mohali 141004, India; sonicasondhi@gmail.com (S.S.); deepaksharma2899@gmail.com (D.S.)
[4] Institute of Agriculture, Punjab Agricultural University, Gurdaspur 143521, India
[5] Department of Chemistry, College of Basic Sciences and Humanities, Punjab Agricultural University, Punjab 141004, India; utrejadivya@pau.edu (D.U.)
* Correspondence: vinayiplrd@gmail.com or vinaykumar.smc@saveetha.com

Abstract: In the past decade, a sudden increase in the number and kind of emerging water contaminants has been observed. The emerging contaminants can be categorized as organic or inorganic. Organic contaminants have been known for years, and techniques for their detection and remediation have been developed. However, inorganic pollutants are much more common. This is because they are detected in very low or negligible concentrations and are equally toxic as organic pollutants at higher concentrations. To boost the research on inorganic pollutant contamination, advancements in detection and quantification techniques are required. The presented paper discusses major inorganic pollutants such as metals and their salts, inorganic fertilizers, sulfides, acids and bases, and ammonia and oxides of nitrogen. In addition, it discusses the inorganic toxicants' toxicity to organisms and the environment, upgraded quantification methods, and advancements in inorganic toxicant mitigation. Moreover, the major bottlenecks in the quantification and removal of inorganic pollutants are discussed at the end.

Keywords: inorganic pollutants; detection and quantification; water pollutants; toxicity assessment; environmental pollution

check for updates

Citation: Kumar, V.; Sharma, M.; Sondhi, S.; Kaur, K.; Sharma, D.; Sharma, S.; Utreja, D. Removal of Inorganic Pollutants from Wastewater: Innovative Technologies and Toxicity Assessment. *Sustainability* **2023**, *15*, 16376. https://doi.org/10.3390/su152316376

Academic Editors: Chang-Gu Lee, Taeil Jang and Hanseok Jeong

Received: 20 July 2023
Revised: 5 September 2023
Accepted: 13 November 2023
Published: 28 November 2023

1. Introduction

Water is a fundamental and essential requirement for the survival of living beings. The health of people and aquatic ecology are both seriously threatened by pollutants in water bodies. There are several types of water pollutants, including pathogens, thermal pollution, radioactive pollution, inorganic pollutants, and organic pollutants [1]. Fresh water is a common drinking-water source in both rural and urban areas, including India (95% of Indians reside in rural regions, and 30–40% live in urban areas). Recent statistics show that more than 1.2 billion people globally lack access to safe drinking water, which is essential for survival [2]. Intensive industrialization and reckless farming practices in recent decades have increased the number of harmful contaminants in groundwater, including inorganic chemicals, heavy metals, radioactive bacteria, and synthetic organic reactants [3]. Arsenic, fluoride, iron, nitrate, heavy metals, and other inorganic pollutants are frequently present in water, and their prevalence in quantities over acceptable limits reduces the water's suitability for living creatures. Pollutants like arsenic, fluoride, and iron are among the pollutants that have a geological origin, whereas other pollutants like nitrates, phosphates, and heavy metals are anthropogenically introduced by factors such as inadequate sewage systems, poorly managed agricultural practices, and industrial discharges. The main factors affecting the degradation of groundwater quality are strong industrial expansion, urban growth, and enormous population increases [4].

Metals (heavy and light) may affect humans and other animals in two different ways: by being present in the environment (air, food, water, and soil) and by experiencing structural changes [3]. There are numerous immediate and long-term harmful consequences of exposure to heavy metals for various human organs. Heavy metals cause toxicity in biological systems through their bonds with sulfhydryl groups and the production of reactive oxygen species (ROS). As a result, several metabolic processes are inhibited, and crucial macromolecules are rendered inactive. Examples of the adverse effects of heavy metal toxicity include cancer, gastrointestinal and renal dysfunction, nervous system diseases, skin lesions, vascular damage, immune system malfunction, and birth abnormalities. The cumulative effects of simultaneous exposure to two or more metals are possible [5,6]. Mortality and morbidity rates are significantly influenced by metal pollution and other substances. According to the World Health Organization (WHO), “environmental variables, particularly exposure to harmful chemicals”, are responsible for more than 25% of the overall burden of illness. The WHO carried out a thorough investigation and determined that 4.9 million fatalities (8.3% of total mortality globally) are linked to environmental exposure and the improper management of certain chemicals [7]. For instance, lead, a heavy metal, is assumed to be responsible for 3% of the burden of cerebrovascular illness globally [8]. Bangladesh, in 2001, reported 9100 deaths and 125,000 disability-adjusted life years (DALYs) due to arsenic-contaminated water [9]. The pollution of groundwater with arsenic, on the contrary, is a common occurrence globally among naturally occurring pollutants. It is known that beyond the WHO guidelines’ threshold of 10 mg per liter, at least 140 million people in 50 countries frequently consume water containing arsenic [2]. The manufacture of chemicals (including metals and their variations) has rapidly expanded over the past several years on a global scale. According to reports, the global output of chemicals has increased by a factor of 10 [8]. A group of five metals (arsenic, cadmium, chromium, lead, and mercury) has been categorized as “known” or “probable” human carcinogens by the United States Environmental Protection Agency (US EPA) and the International Agency for Research on Cancer (IARC), respectively [10].

The physical water shortage in the world today is a result of insufficient natural water resources to meet local demand, as well as ineffective management of the water resources already at hand. The prevalence of the most hazardous environmental toxin sources is overlaid on the graph below. These include radionuclides, pesticides, and heavy metals, including lead, mercury, and chromium [2]. Integrated and growing water purification techniques are immediately recognized for their ability to offer convincing answers to the water-pollution issue. Consequently, more methods for wastewater treatment as well as purification are now easily accessible. The existing technologies for purifying water are touted to have an efficiency of more than 99%. However, this is only true under idealized conditions of pH, contaminant concentration, and other operating parameters. In fact, under industrial-scale conditions, their efficiency may decrease significantly, down to 90% or less [11]. Additionally, and probably more crucially, many of these treatments, like ion-exchange resins, are made to target a single pollutant at a time, making it impossible for them to be used in highly damaged environments where many contaminants are almost always present at once. Most of the technologies that are currently accessible are unaffordable, and sometimes those that are the cheapest can result in secondary pollution [12].

One study focused on the impact of heavy metal exposure on the prostate using murine models and discussed toxicity mechanisms. Another study focused on the high risk of heavy metal contamination in vegetables. Another still incorporated bioaccessibility and toxicity into an accurate health risk assessment, and one other focused on an ecological risk assessment of potentially toxic heavy metals in sediments in El Burullus Lake, Egypt. These studies demonstrate that heavy metals are detrimental to human health, and strategies for their removal should be designed [13–17].

Figure 1 presents different types of inorganic pollutants present in water and their sources of origin.

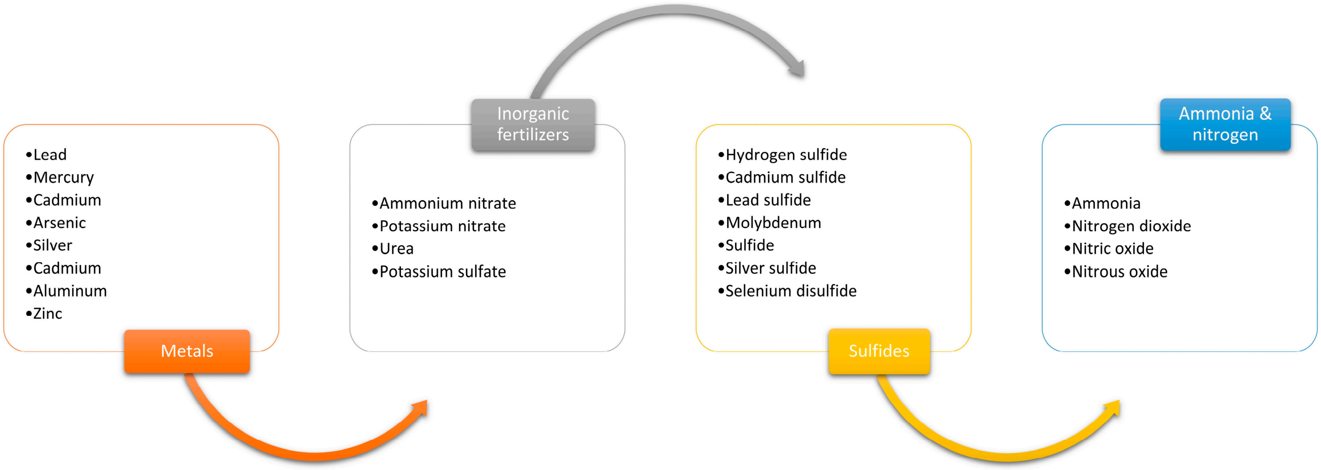

Figure 1. Different types of inorganic pollutants present in water.

The presented literature review is focused on understanding different types of inorganic pollutants and their physiochemical properties. In addition, it discusses the recent advancement in the detection and quantification of inorganic pollutants in the water. Moreover, it discusses the toxicity imposed by inorganic pollutants and the challenges faced in the removal of these pollutants. At the end, a conclusion is made based on the current literature review.

2. Inorganic Toxicant Toxicity to Organisms and the Environment

Heavy metals, nutrients, sediments, and industrial waste are examples of inorganic pollutants. The increase in anthropogenic activities and the set-up of industries related to mining, agriculture, etc., has increased the emergence of these environmental contaminants. These environmental contaminants are present in different water bodies [18–22]. These contaminants are responsible for cancer and other microbial diseases due to properties such as bioaccumulation and non-biodegradability of these pollutants have been developed, which demonstrate a continuous rise in their concentration [23–25].

Inorganic pollutants are often made up of inorganic byproducts that result from radiant radiation, noise, heat, or light. In general, inorganic contaminants include arsenic, cadmium, lead, mercury, chromium, aluminum, nitrates, nitrites, and fluorides. Most of them possess an extended tenacity and resistance to deterioration [26–29]. The primary components of inorganic pollutants are connected to operations like mining and the burning of fossil fuels, municipal solid waste, industrial waste, and fertilizers. There are various types of inorganic pollutants in water that are responsible for various diseases and other comorbidities. Figure 2 presents a schematic presentation of inorganic pollutant types, their quantification methods, and their removal technologies.

2.1. Sulfur Dioxide

Inorganic chemical sulfur dioxide is a heavy, colorless gas that is very toxic. It is created in enormous amounts during the transitional stages of the production of sulfuric acid. The stench of sulfur dioxide is as strong and unpleasant as that of a freshly struck match. Sulfur dioxide, which naturally occurs in volcanic gases and solution in the waters of some warm springs, is often made commercially by burning sulfur or other sulfur-containing compounds like iron pyrite or copper pyrite in air or oxygen. When sulfur-containing fuels are burned, significant amounts of sulfur dioxide are produced. It may interact with water vapor in the atmosphere to generate sulfuric acid, a main ingredient in acid rain [30,31].

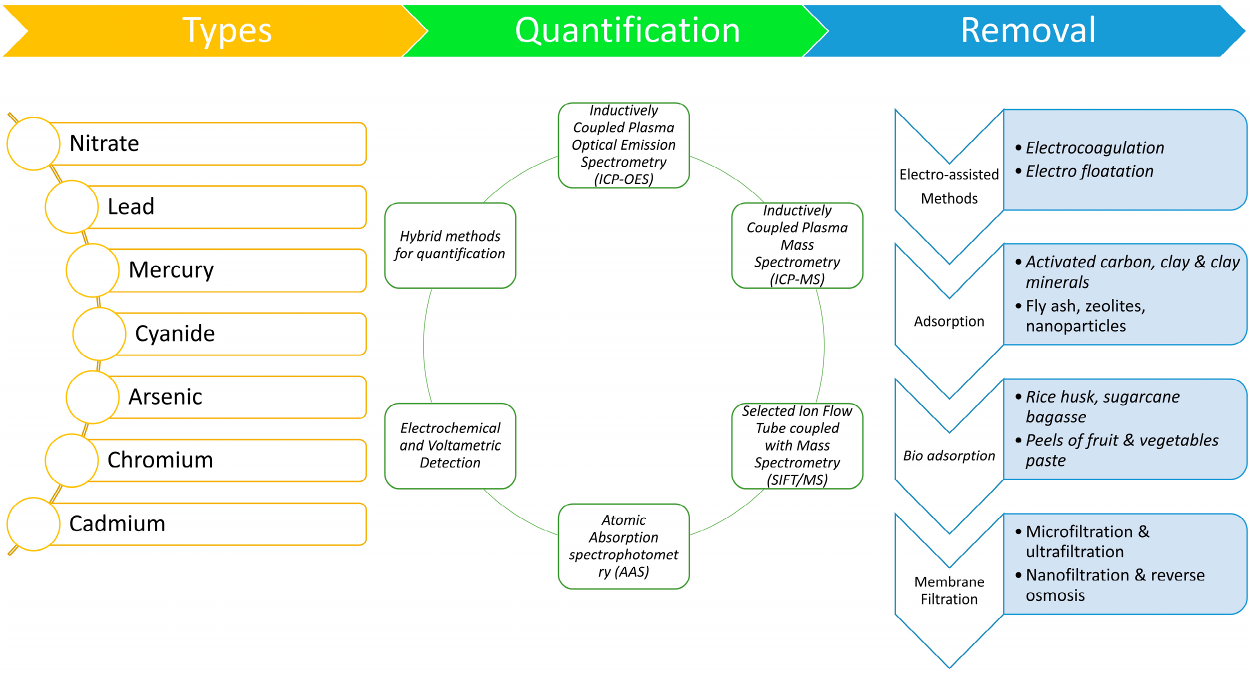

Figure 2. Inorganic pollutant types, their quantification methods, and their removal technologies.

2.2. Nitrate Salts

Worldwide concern has been raised over nitrogen poisoning of groundwater, especially in regions of intensive agriculture. The primary inorganic nitrogen molecules (NO_3^-, NH_4^+, and NO_2^-) in excess in drinking water have been said to be harmful to human health. Due to the variety of nitrogen sources and the intricate interactions between affecting environmental elements, the mechanism behind the synthesis of inorganic nitrogen compounds in groundwater is complicated. The inorganic nitrogen compounds in groundwater have been linked to domestic and industrial pollution [32]. By preventing hemoglobin from delivering oxygen, ingested nitrites and nitrates from contaminated drinking waters can cause methemoglobinemia in people, especially in newborn babies. Through their involvement in the creation of nitrosamines, ingested nitrites and nitrates may also contribute to the emergence of gastrointestinal malignancies [21,32].

2.3. Lead Salts

Lead is frequently found in ore together with zinc, silver, and copper. Metallic lead is often present in nature and may enter the body by inhalation of air as well as absorption of food, drink, and soil matrixes. Lead usually enters the body through the blood, soft tissues, and bones. It has a variety of health problems, including harm to the neurological system, liver, and kidneys. Numerous neurological conditions, including mental retardation and behavioral issues, are brought on by excessive lead ingestion. The central nervous systems of developing children and infants are also harmed by the metal. Additionally, it raises the risk of heart disease and elevated blood pressure [30,33].

2.4. Mercury Salts

It has long been understood that mercury contamination is detrimental to the environment and human health. Mercury concentrations in water and soils have been steadily rising in recent years because of industrial activity and long-term atmospheric transport [34]. When utilized at high levels, mercury is exceedingly dangerous. It is present in a variety of water-polluting agents, including large-scale gold mining, the primary production of nonferrous metals, and the burning of fossil fuels. This element is also present in trace amounts in the chloro-alkali sector, polluted areas, waste from consumer items, and cement manufacture [35].

2.5. Zinc Salts

Zinc is often employed as a corrosive material in alloys, dry-cell batteries, paint, plastics, wood preservatives, rubber, cosmetics, and other products. The water may become contaminated by the waste from connected industry. Waste contaminated with zinc can also be found in processes including metal processing, burning coal, and replacing worn-out tires on cars. In contrast to the physiological and toxic effects of excess Zn in humans, which include vomiting, dehydration, electrolyte imbalance, stomach discomfort, nausea, drowsiness, and lack of coordination. An excess Zn in plants results in chlorosis and stunted growth. As a result, the allowable quantity of zinc in drinking water is set at 3 mg/L to guarantee that there is enough to fulfill body demands without running the danger of build-up and toxicity [30,36]. Manufacturing processes like steel manufacture or mining are the primary sources of Zn discharge into sewage or soil ecosystems [36].

2.6. Cyanides

Mining and metallurgical industries use around 13% of the 1.1 million metric tons of hydrogen cyanide that are generated annually globally. Therefore, industrial effluent from the mining, metallurgical, petrochemical, or coking industries includes free cyanide. Gold and silver are typically extracted from crushed ores using cyanide solutions in mining procedures. They might also be employed to extract other metals, including copper, lead, and zinc. Because of its capacity to bind iron in the blood by creating complexes and its tendency to suffocate animals, cyanide is thought to be an extremely dangerous toxin [37]. A total of 1–3 mg/kg of body weight is LD 50 for those exposed. It has been extensively documented over the past ten years that conventional technology may remove cyanide from industrial effluent. Under aerobic circumstances, cyanide may be broken down by microbes to ammonia, or it can be oxidized by potent oxidizers such as hydrogen peroxide, hypochlorite, and ozone to less hazardous cyanate [37,38].

2.7. Arsenic Salts

Arsenic poisoning has raised concerns on a global scale because of its toxicity and serious harm to both humans and the environment. The creation of effective adsorbents to remove arsenic pollution is urgently needed [39]. Arsenic is released into the environment when fossil fuels are burned, as well as when fly ash and coal cleaning waste are disposed of and leached into groundwater. However, it is understood that arsenic is dangerous if consumed in excess. It can result in ulcers and chronic conditions in the bladder, kidneys, and lungs. It can also cause skin cancer. The peripheral nerves and blood vessels are also damaged. For instance, drying chili pepper over open flames while cooking and heating with coal that has 35,000 ppm of arsenic might result in chronic arsenic poisoning. Arsenic in chili peppers, which already have a 1 ppm arsenic content, can increase to 500 ppm after drying. Nearly 3000 people have displayed arsenic poisoning signs, including cell cancer, Bowen's disease, and hyperpigmentation [30,39,40]. Arsenic has been effectively removed using membrane technologies such as reverse osmosis and nanofiltration. Further research is needed to determine the effectiveness of these technologies in handling actual polluted sources that contain different species [40].

2.8. Chromium Salts

Chromium is often used in industrial settings as a heavy metal for alloys, chromium plating, and wood anti-corrosion [41]. Chromium (Cr) in soil is found in the valence states of Cr(VI) and Cr (III). Cr(VI) has greater toxicity than Cr(III) due to its high dissolution, mobility, mutagenicity, and carcinogenicity. Chromium has been discovered to be harmful to the liver and spleen when consumed [41,42].

2.9. Cadmium Salts

Cadmium (Cd) is a divalent, bluish-white, soft, and ductile metal that has no fragrance or flavor. Eight isotopes of it are present naturally [43]. Cd has two possible oxidation states: -1 and +2. Out of the two, the +2 valence is most prevalent. Brown CdO is produced when Cd oxidizes in humid air. Sphalerite (zinc sulfide) serves as the most prevalent commercial source of Cd, which is mostly found in Zn ores in the environment [44]. In both terrestrial and marine creatures, Cd exhibits biological activity and is known to be very harmful to humans and other living things. Several human activities and environmental pollutants release cadmium into ecosystems [45]. The human body is harmed by Cd toxicity in different organs. However, it concentrates most severely in the kidneys and leads to major problems such as kidney stones, pulmonary emphysema, and damage to the renal tubules [30,46].

2.10. Copper Salts

Copper is a crucial component for both industry and the natural environment. When compared to optimal values, the concentration of Cu^{2+} ions in living organisms either rises or falls, depending on the toxicity of copper [47]. Cu(II) in potable water is only allowed in concentrations between 1.0 and 2.0 mg/L [47]. Due to its non-degrading feature, which destroys liver cells and causes nerve damage, it has a malignant effect at concentrations above the allowed range [48]. Effluents from the mining, electroplating, smelting, metal processing, chemical catalysis, photographic, electrical, and electronic sectors frequently include copper [49].

3. Advances in Inorganic Pollutant Detection

Inorganic pollutant detection and quantification requires sophisticated instruments. In addition, analysis and comparison of the obtained result is a crucial part. In recent decades, several techniques have been developed for their identification. Discussed below are some of the important techniques used in the quantification of the inorganic pollutants in the water. Table 1 presents the different methods for the determination of heavy metals.

Figure 3 presents methods available for quantification of heavy metals.

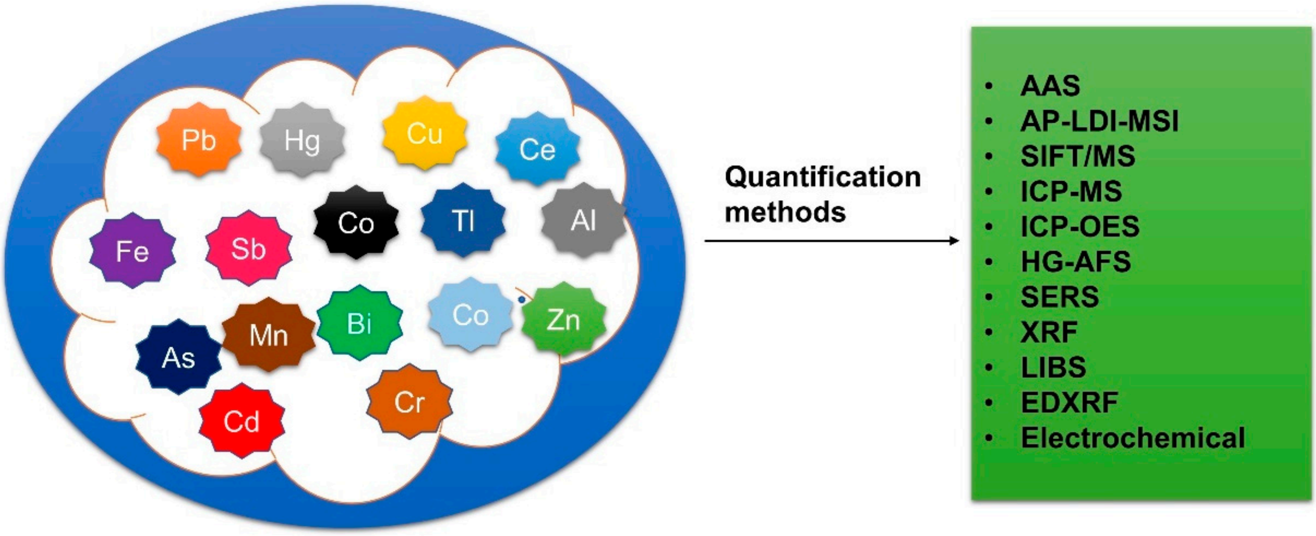

Figure 3. Quantification methods for heavy metals.

Table 1. Different quantification methods for heavy metals with limit of detection (LOD) and limit of quantification (LOQ).

Method of Quantification	Sub-Type of Quantification Method	Elements Detected	LOD and LOQ
AAS	FAAS	Calcium	1.6569 and 5.5232 mg/kg
	FAAS	Cadmium	i.e., 0.0150 and 0.0499 mg/kg
	Electrothermal AAS with μ-EME	Chromium (IV)	0.003 and 0.010 ng/mL
	HR-CS-FAAS	Cadmium	1.3 and 4.3 μg/L
	HR-CS-EFAAS	Cadmium, Iron, Nickel	LOD = 3.2 ng/g, 2.2 μg/g and 0.0444 μg/g LOQ = 10.8 ng/g, 7.4 μg/g, 0.148 μg/g.
	GFAAS	Manganese, Lead	1 μg/dL
	SQT-FAAS	Palladium	6.0 and 20.0 μg/mL
	SQT-FAAS	Silver	40 and 130 ng/L
	SQT-FAAS	Rhodium	0.3 and 1.1 μg/L
	SP-MNPs-LDSPE-SQT-FAAS	Bismuth	6.0 and 21.0 μg/L
AP-LDI-MS		Aerosol particles	30 μg
ICP–MS	IC-HR-ICP–MS	Arsenic	0.3 and 1.1 pg
	ICP–MS	Chromium (IV)	0.023 and 5 μg/L
ICP–OES		Cadmium	51.9 and 78.9 μg/mL
		Lead	33.7 and 102.1 μg/mL
		DMA	0.30 and 0.39 μg/kg
		MMA	0.34 and 0.46 μg/kg
XRF		Lead	0.6 mg/kg
EDXRF		Arsenic	0.3 to 0.5 mg/kg
Electroanalytical method		Lead	6.7 and 22 μg/L
		Mercury	7.5 and 25 μg/L

3.1. Atomic Absorption Spectrophotometry (AAS)

The detection of heavy metals such as antimony (Sb), chromium (Cr), bismuth (Bi), copper (Cu), cerium (Ce), arsenic (As), cadmium (Cd), gold (Au), calcium (Ca), iron (Fe), and lead (Pb) is immensely feasible with the help of AAS along with gas chromatography (GC) [50,51]. The estimation is quite efficient due to the quantitative and qualitative estimation of various constituents present in the tested sample. It was reported that the Flame atomic absorption spectrophotometer (FAAS) for Ca showed a higher limit of detection (LOD) and limit of quantification (LOQ), i.e., 1.6569 and 5.5232 mg/kg. However, LOD and LOQ values were observed to be quite low for Cd, i.e., 0.0150 and 0.0499 mg/kg. The study showed the linearity for the studied toxic metal standard solutions in the range of 0.02–0.4 mg/kg for Cd, and for Ca, it was found to be 11–100 mg/kg. The correlation value (R^2) was found to be in the range of 0.9971 for Cr to 0.9999 for Ca.

A study carried out the quantification of Cr(VI) using electrothermal AAS. For the extraction of Cr(VI) selectively from tested samples [52]. They used the electro-membrane extraction (EME) method along with micro-EME (μ-EME). The study was carried out on fish samples, *Ocimum basilicum*, and milk powder. The EME method, along with μ-EME, afforded 73.7% Cr (VI). The experiment showed a linear range value from 0.01 to 5.0 ng/mL with LOD and LOQ, i.e., 0.003 and 0.010 ng/mL, respectively, with 584 enrichment factors. A recent study carried out quantification of Cd in water samples using cloud-point extraction (CPE) along with high-resolution continuum source flame atomic spectrometry (HR-CS-FAAS) [53]. It showed a linear range from 5.0 to 75.0 μg/L with LOD and LOQ values 1.3 and 4.3 μg/L, respectively. Another study showed the method for the determination of toxic elements using high-resolution continuum source electrothermal flame atomic spectrometry (HR-CS-EFAAS) [54]. The study showed the LOD values of 3.2 ng/g, 2.2 μg/g, and 0.0444 μg/g for Cd, Fe, and Ni, respectively. LOQ values for Cd, Fe, and Ni were found to be 10.8 ng/g, 7.4 µg/g, and 0.148 µg/g, respectively. The recovery rate was found to be 93 to 100%.

Some researchers have developed the graphite furnace atomic absorption spectrometry (GFAAS) analytical method for determining manganese (Mn) and Pb in a target sample [55]. It was reported that the developed method showed linearity in the range from 0.001 to 0.015 and from 0.002 to 0.020 µg/L for Mn and Pb, with a recovery rate from 84.80% to 107.98%, respectively. GFAAS is helpful in the determination of samples at volumes of 5 and 20 µL. Another study reported the determination of lead with GFAAS with an LOD value of 1 µg/dL [56].

Slotted quartz tube flame atomic absorption spectrometry (SQT-FAAS) is another technique used for the determination of palladium (Pd) from metal waste [57]. This method was used along with sieve-conducted two-syringe pressurized liquid-phase microextraction (SCTS-PLPME) to increase the surface area for extraction purposes. The designed method showed a linear range from 20 to 1000 µg/mL with LOD and LOQ values of 6.0 and 20.0 µg/mL. Similarly, researchers carried out the determination of silver in metal waste samples by SQT-FAAS technique along with steric acid-coated magnetic nanoparticle-based solid-phase microextraction (SA-MNP-SPME) [58]. The use of iron oxide along with steric acid contributes to surface area enhancement and applied magnetic field for the separation of pollutants from the liquid phase. The designed method was reported to be 305 times more efficient in the detection of pollutants. The recovery rate was found to be 96.3 to 105.1%, as shown by the matchmaking calibration. The LOD and LOQ values were found to be 40 and 130 ng/L, as shown by the developed method. Another study reported the determination of rhodium (Rh) pollutants using the SQT-FAAS technique along with extraction by solid-phase microextraction method (MNP-SPME) [58]. The designed method was reported to be 129.1 times more efficient in the detection of rhodium pollutants. The recovery rate was found to be 95.5% to 102.9%, as shown by the matchmaking calibration. The LOD and LOQ values were found to be 0.3 and 1.1 µg/L, as shown by the developed method. A study reported the use of FAAS along with microextraction by the solvent-liquid-phase microextraction (SS-LPME) of Nickelnickel [59]. The designed method was reported to be 40 times more efficient in the detection of nickel trace pollutants, as compared to FAAS, with a 91 to 98% recovery rate.

In a study, researchers combined two techniques—ligand-less dispersive solid-phase extraction (LDSPE) and SQT-FAAS—for the determination and detection of bismuth in the tested sample [60]. It is presented as a single study with combined analytical techniques known as SA-MNPs-LDSPE-SQT-FAAS. The study showed linearity in the range from 20 to 250 µg/L along with LOD and LOQ values of 6.0 and 21.0 µg/L. The developed method was reported to be 94 times more efficient in the detection of bismuth from tested urine samples, with a recovery rate of 95% to 101%. Another application of the SQT-FAAS system is in the determination of cadmium [61]. Tekin and co-workers carried out solid-phase extraction (SPE) of wastewater samples using zirconium nanoparticles. The study showed a linearity curve in the range from 2.0 to 25 µg/L along with LOD and LOQ values of 0.44 and 1.46 µg/L [61]. The developed method was reported to be 94 times more efficient in the detection of bismuth from tested urine samples, with a recovery rate of 96.1% to 100.7% and a 0.9993 regression coefficient. Some researchers have carried out the quantification of calcium, magnesium, sodium, iron, potassium, and zinc in mango fruit and its juice [62]. The values of Cd determined by AAS in fruit and juice were 8.45 and 1.30 µg/L, respectively. A research group developed a highly efficient and accurate method for the determination of cadmium by the combination of dispersive solid-phase extraction (DSPE) based on magnetic nickel particles and SQT-FAAS [63]. The study showed LOD and LOQ values of 0.58 and 1.93 µg/L. The developed method was reported to be more efficient in the detection of Cd from tested urine samples, with a recovery rate of 93.8 to 108.2%. A study demonstrated that atomic spectrometry could also be used for arsenic detection [64].

3.2. Selected Ion Flow Tube Coupled with Mass Spectrometry (SIFT/MS)

A study quantified hydrogen sulfide using SIFT/MS [65]. It was found that the employed system was extremely sensitive to water content as it negatively affects the hydrogen sulfide calculations. It was reported that a 50 ppb concentration of H_2S at 4.0% vol humidity is essential for measuring H_2S in the SIFT/MS technique.

3.3. Inductively Coupled Plasma–Mass Spectrometry (ICP–MS)

This is a multi-element analysis quadrupole, highly precise technology with inductively coupled plasma as an ion source and mass spectrometry. This can immediately measure the mass of target elements without any interference, and displays wide linearity. The ionization of plasma helps this technique to detect and quantify toxic element concentrations to the microgram/liter. The major characteristic of this spectrometric technology is the analysis of more than 70 elements at one time [66]. Researchers have developed the microwave coupled with ion chromatography (IC) method for As separation along with its detection with high-resolution inductively coupled plasma–mass spectrometry (IC-HR-ICP–MS) [67]. The method can detect and quantify arsenic to a lower limit of 0.3 to 2.6 pg/g and 1.1 to 8.6 pg/g, respectively. The extraction of arsenic was conducted using the gradient elution method with 0.5 mM HNO_3 at pH 3.4 and 50 mM HNO_3 at pH 1.4.

A research group carried out the determination of Cd by coupling ICP–MS with a chelate-enhanced nebulized film dielectric barrier discharge (NFDBD) vapor generation sampling system [68]. The developed system used sodium diethyldithiocarbamate (DDTC) as a chelating reagent. It shows high sensitivity for Cr (VI), i.e., 10.5 times more than the traditional methods used. The LOD and LOQ values for Cr(VI) were found to be 0.023 and 5 $\mu g\ L^{-1}$. Its major advantage was the appreciable detection limit and the elimination of reducing agents, along with being operatable at a low power of ≤ 65 W. A study coupled HPLC with ICP–MS for the determination of trace pollutant levels in food samples [69]. The developed method showed LOD and LOQ values (µg/kg) of 0.0830 and 0.274 for Cd, 0.0521 and 0.172 for Pb, 0.0669 and 0.221 for total As, 1.12 and 3.72 for As^{3+}, 2.38 and 7.94 for As^{5+}, respectively. The HPLC technique, coupled with online detection using inductively coupled plasma–mass spectrometry, plays an essential role in the separation and quantification of arsenic species [70]. HPLC coupled with the inductively coupled plasma–mass spectrometry method was used for arsenic quantification [71]. It was observed that arsenic was a major fraction of particulate matter, with 78.7 to 78.9% in different matters studied. A study reported the use of HPLC-ICP–MS technology for the determination of arsenic in contaminated soil [72]. The study reported different limits of quantification for different arsenic species. There was a 0.047, 0.082, 0.168, and 0.167 µg/g quantification limit for As(III), dimethylarsenic acid (DMA), monomethylarsenic acid (MMA), and As(V). Apart from the quantitative and qualitative estimation of toxic elements, ICP–MS is also used for tracking the cellular transformation of toxic targets to understand metabolic and biological pathways [73].

A research group reported the quantification of different arsenic species, such as MMA, DMA, and arsenobetaine (AB), using HPIC/ICP–MS [74]. The method employed showed a good linear range with a coefficient of regression of 0.999. The limits of quantification for the method were reported as 0.075, 0.241, 0.235, and 0.321 ng/g for iAS, MMA, DMA, and AB, respectively.

3.4. Inductively Coupled Plasma Optical Emission Spectrometry (ICP–OES)

This is another developed method for precise analytical efficiency and the determination of toxic trace metals in evaluated biological samples. The instrument was reported to show LOD values of 51.9, 47.33, 33.7, and 20.7 µg/mL for Cd and Pb for axial and radial view. Along with this, it also showed LOQ values of 78.9, 143.3, 102.1, and 62.8 µg/mL for Cd and Pb for axial and radial view [68]. Nawrocka et al., 2022 [75] developed a fast and effective method for the isolation of total arsenic, arsenite, As(III), arsenate As(V), arsenobetaine (AsB), arsenocholine (AsC), MMA, and DMA. The measurement of concentrates was taken using ICP–MS coupled with a microwave-assisted extraction method. The quantification was performed using ICP–MS in one chromatographic run using ammonium carbonate-based buffers, which do not affect ICP–MS sensitivity. The method reported LOD values of 0.31, 0.29, 0.30, 0.34, 0.27, and 0.52 µg/kg for AsB, AsC, DMA, MMA, As(III), and As(V), along with LOQ values of 0.41, 0.38, 0.39, 0.46, 0.42, and 0.92 µg/kg for the latter-mentioned. A researcher used a gas chromatography–flame ionization detector (GC–FID), GC–MS, and ICP–OES to measure the concentration of heavy metals [52]. Along with that, phase contrast microscopy (PCM) was used to identify the properties of asbestos fibers. A researcher for the determination of arsenic with high sensitivity in the field used ICP–OES along with the microwave digestion method [76]. The amount of arsenic detected was 0.46 to 0.81 µg/g. De Mello et al. (2022) [77] carried out the determination of several toxic elements such as aluminum, calcium, copper, chromium, iron, potassium, magnesium, manganese, sodium, nickel, phosphorus, lead, tin, silicon, and zinc by employing the ICP–OES technique.

3.5. Hybrid Methods for Quantification

Pandey et al. (2022) used a fuzzy comprehensive model for the quantification of toxic water pollutants [78]. The major purpose of the study was to evaluate the water quality index (WQI) by considering both freshwater and seawater. The pollutants were considered to be variables and studied as a multivariate problem. However, this model was not able to categorize water standards as good or bad. There was no judgment on the quality of the water. Researchers carried out the quantification of mercury using the thermal-decomposition technique in combination with a direct mercury analyzer (DMS) in South Africa [79]. The recovery rate was found to be 84 to 99%. A study synthesized fluorescent probe-based 1,8-napthalimide for the detection of fluoride ions [80]. A research group quantified various inorganic pollutants, such as sulfates and Cl^-, through positive matrix factorization (PMF) coupled with the health risk assessment (HRA) model [81]. Researchers synthesized metal-organic framework-NH_2-MIL-53 (Al)-based adsorbents for the detection and removal of various toxic pollutants such as lead (Pb^{2+}), copper (Cu^{2+}), mercury (Hg^{2+}) and cadmium (Cd^{2+}) [82]. MIL-53 is also reported with adsorption of CO_2 and is known to show a breathing effect [83]. A research group carried out total arsenic and arsenic speciation by hydride generation atomic fluorescence spectrometry (HG–AFS) and HPLC-HG-AFS [84].

3.6. Electrochemical and Voltammetric Detection

This is employed as a relevant method for the on-site detection of heavy metals due to its high sensitivity [85]. Among electrochemical techniques, differential pulse voltammetry (DPV) and square-wave voltammetry (SWV) are widely employed techniques. Surface modification is an important part of electrodeposition, physisorption, and chemisorption. A research group developed an electrochemical sensor using a glassy carbon electrode (GCE) for the detection of Cd^{2+} and Pb^{2+}. The GCE was modified with a hexagonal lanthanide known as MOF, ZJU-27 [86]. It was observed that the developed method showed high sensitivity, as it showed sensitivity towards Pb^{2+} with an LOD value of 0.228 pb. Similarly, another study that modified GCE also helped in the sensing of Cu^{2+} ions [87]. It was found that modified electrodes showed high linearity in the range of 10–100 mV/s with the least sensing limit value 1×10^{-5} M. A study used bismuth for the modification of electrodes for the detection of aluminum ions from tested samples [88]. The developed method showed a linear range from 1.85×10^{-10} to 3.75×10^{-6} mol/L with 0.025 pb as the detection limit. It was observed that the developed method was completely resistant to lead, zinc, and cadmium ions. Researchers carried out the detection of mercuric(II) ions using GCE modified with tribenzamides and silver nanoparticles [89]. It was reported that the developed method was able to detect target ions even at a femtomolar concentration, which represented the high sensitivity and reproducibility of the method. A research group carried out the voltammetric detection of toxic metal ions by employing an electrochemical sensor [90]. A 2-(Anthracen-9-yl)benzothiazole-modified graphene oxide–nickel ferrite-reduced graphene oxide sensor was developed for the detection of chromium, copper, and mercury ions. The developed method showed excellent linearity in the range of 0.05 to 1250 nM with LOD values 123, 54.1, and 86.6 pM for chromium, copper, and mercury ions, respectively. A study used GCE modified with boron–nitrogen-doped carbon for the detection of toxic pollutant ions in the sample [69]. The study was carried out using square-wave anodic stripping voltammetry. It was observed that the developed method showed electrochemical responses at low values of 0.459 and 0.509 for cadmium and lead ions, respectively. A study synthesized an electrochemical device to measure the sensitivity of Cd^{2+} [91]. The designed device used GCE modified with Prussian blue (PB) poly-(3,4-ethylenedixoythiophene) polystyrene sulfonate (PEDOT)-loaded laser scribed graphene (LSG). This electrochemical device worked through cyclic voltammetry. The designed device showed linearity in the range of 1 nM–10 µM and a detection limit of 0.85 nM.

A research group carried out the detection of nitrite with the help of a non-enzymatic electrochemical method [92]. In this study, various organic and inorganic nanocomposites of polyaniline MnO_2 were synthesized for detection purposes. A study synthesized nanocomposites comprised of carbon-supported Ni, Zn, or Cu manganate for the detection of heavy metals [81]. It was observed that the designed electrochemical system linearity was in the range of 1.4–7.7 µM for lead and 0.7–6.7 µM for mercuric ions. The system showed a 0.050 µM detection limit for lead ions and 0.027 for mercuric ions. In another study, the design of a highly accurate system, known as a voltage-controlled circuit for the detection of cadmium and lead ions, was reported [93].

4. Recent Advancements in Inorganic Toxicant Mitigation

Several water treatment techniques are available based on water treatment techniques and their classification into traditional procedures, established techniques, and active research areas [94]. Each treatment technique has advantages and disadvantages in terms of cost, efficiency, practicality, and environmental effects. Figure 4 discusses the major inorganic toxicant removal technologies.

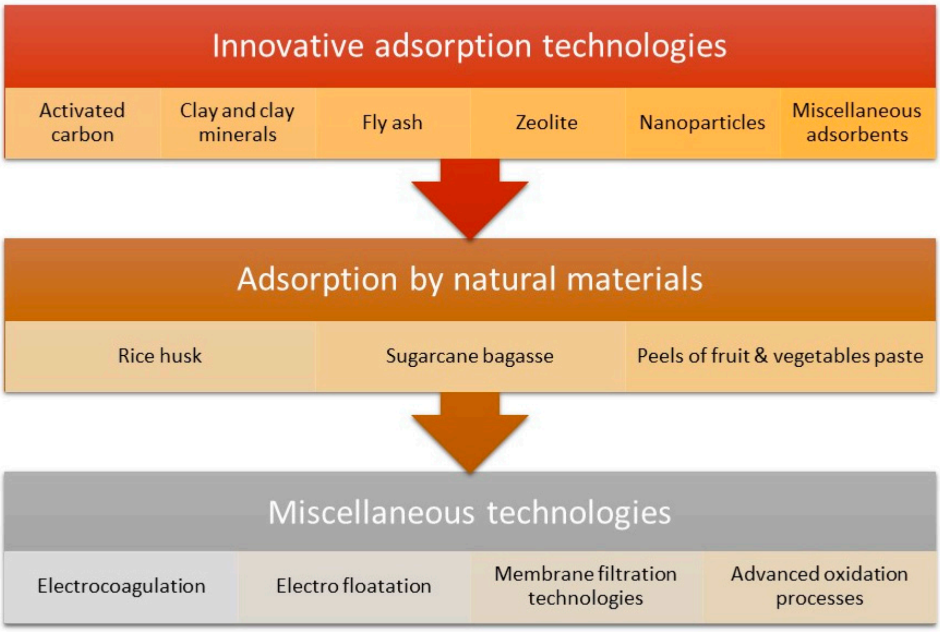

Figure 4. Inorganic toxicant removal technologies.

Some of the efficient technologies for the removal of inorganic pollutants from water are discussed here.

4.1. Electro-Assisted Methods

To treat water and wastewater, electrochemical processes, including electrocoagulation, electro floatation, electrodialysis, and electrooxidation, can be utilized.

Electrocoagulation and Electro Floatation

Colloidal particle coagulation in an aqueous media caused by the introduction of an electric current is known as electrocoagulation [95]. During this process, contaminants are suspended, emulsified, dissolved, and rendered unstable. The cathode generates hydrogen, and the bubbles aid in the elimination of contaminants [96]. The following elements support the adoption of electrocoagulation for the purification of water. The production of coagulants in situ lowers the price of transporting chemicals and imposes storage limitations in large-scale applications [97]. In contrast to chemical coagulation, electrocoagulation does not enrich the effluent with anions and salts, leading to the production of compact sludge. Since electrocoagulation produces effluent with an almost-neutral pH, post-treatment for pH neutralization is omitted [96]. When water is electrolyzed, the cathode and anode electrodes produce hydrogen and oxygen gas bubbles, which are used to remove pollutants from the water. Pollutants cling to the bubbles and rise to the top, where they are skimmed off on a regular basis. The efficiency of the process is determined by the size of the bubble. The smaller the size of the bubble, the more effectively it is removed [98]. Even though electrochemical methods are efficient at eliminating inorganic pollutants, they are subject to several drawbacks, including high energy consumption, higher treatment costs, and the need for periodic electrode cleaning. This is because electrode scaling decreases process efficiency and difficulties with sludge disposal. However, chemical treatment might not be technically or financially viable for some of the pollutants that are highly toxic in the effluent [98]. A study proposed a new concept of unimpeded and selective full-cell anion-cation separation using a custom-designed anion-kinetics-selective anode and cation-energy-selective cathode for water treatment. The study discusses the importance of differences in ion absorption energy along with the anion kinetics and cation selectivity. The study demonstrated that the technology can be used for wider application areas.

4.2. Innovative Adsorption Techniques

4.2.1. Activated Carbon, Clay, and Clay Minerals

Activated carbon can be prepared from abundant raw materials. Due to its adaptability, several researchers have tried to employ activated carbon to reduce costs by producing carbon from inexpensive sources or by altering the surface. Cu, Zn, and Cr were removed more successfully using modified activated carbon made with sodium diethyl dithiocarbamate and tetra butyl ammonium iodide [99].

For the removal of metal ions from water, a variety of clays and clay minerals are utilized as adsorbent materials. Clay minerals can absorb metal ions because of the gaps between their layers. Clays expand in an aqueous solution to make room for water and ionic species [100]. The benefits of employing clay as an adsorbent include its affordability, availability in the area, substantial specific surface area, exceptional characteristics for adsorption, nontoxicity, and considerable ion-exchange potential [101]. In many instances, pretreatment is necessary to increase clay capability for adsorption. Numerous investigations on the removal of heavy metals by natural clays proved effective. According to research on the removal of Cu(II) from cachaca, a removal efficiency of 68.7% could be reached after 120 min of equilibration time [101].

For the removal of As(V) from the aqueous solution, Moroccan clay materials were investigated. Modified clays were employed because of their improved removal efficiency. It was observed that chromium could be removed with 99.5% effectiveness using cellulose–clay biopolymer composite [102]. A special clay with titanium pillars that was laden with iodine potassium was developed to remove mercury [102]. As hybrid organic–inorganic nanomaterials, interest is growing in nano-clay composites, including polymer clay nanocomposites and organically modified clays. Clay mineral effectiveness is on par with that of activated carbon; the issue of recovering adsorbent from filters after usage must be solved. Researchers are also interested in nano-clay due to its ability for selective adsorption [103].

4.2.2. Fly Ash

Fly ash has been employed as an adsorbent by several researchers to manage wastewater [104]. Due to its chemical makeup as well as its physical characteristics, including surface area, porosity, and particle size distribution, fly ash has a potential use in the treatment of wastewater [105]. Research has been conducted to see how well fly ash works to remove Zn and Ni through adsorption. Successful mercury removal using fly ash has been demonstrated, and it has been observed that coal fly ash's adsorption capacity is on par with that of activated powdered charcoal [105]. After the heavy metals are absorbed, fly ash may readily solidify, but the issue of leaching must be considered and assessed.

4.2.3. Zeolites

Zeolites are natural substances that may be found in many deposits and can also be created synthetically so that their characteristics can be modified for certain uses. Zeolites are extremely crystalline aluminosilicate substances made of oxygen bridges connecting Si or Al atoms [94]. Zeolites are useful for removing heavy metals from wastewater because they contain exchangeable ions. Natural zeolite was examined for its potential to remove Fe from synthetic mine fluids with Pb, Cd, and Zn. The study was conducted on the use of artificial zeolite manufactured from coal fly ash to remove polluted fluid containing Cr, Pb, Ni, Cu, Cd, and Zn [106]. Synthetic zeolites were also assessed as an adsorbent for the removal of copper, lead, zinc, nickel, iron, and arsenic. Synthetic zeolite was efficient in removing zinc and cadmium ions [107].

4.2.4. Nanoparticles

Nanoparticles have generated a lot of attention as adsorbents because of their catalytic potential, high reactivity, vast surface area, compact size, ease of separation, and multiple active sites for interacting with various pollutants. The most often utilized materials that have been employed as adsorbents include nanomaterials such as nanoscale zerovalent iron, Fe_2O_3, Fe_3O_4, TiO_2, SiO_2, and Al_2O_3. Iron oxide nanoparticles are the focus of much research because of their unique qualities, applications, superparamagnetism, nanosize range, and high surface area-to-volume ratios [108]. Titanium dioxide is the focus of research because of its potent nontoxicity, great stability, photocatalytic activity, and remarkable dielectric characteristics. When used as a catalyst in chemical processes, nano alumina performed well and showed remarkable resistance to chemical agents [109].

Metal ions from cadmium, copper, chromium, lead, and mercury can be removed using nano alumina. Additionally, alumina nanoparticles have a high surface area, are economical, and have outstanding thermal stability. Additionally, hybrid nanoparticles are effective at removing heavy metals from water. Composite materials based on graphene oxide are also receiving much interest as a means of cleaning up water pollutants. On a modified Torlon hollow fiber support, an ultrathin graphene oxide framework layer was applied layer by layer to create a composite membrane with excellent nanofiltration (NF) performance to remove Pb21, Ni21, and Zn21 [3].

Heavy metals were removed from water using graphene oxide-based microbots that had nanosized multilayers of nickel, platinum, and graphene oxide materials. To remove dyes and heavy metals, new magnetic bio-sorbent hydrogel beads were created utilizing graphene oxide, modified biopolymer gum tragacanth, and polyvinyl alcohol. Since nanoparticles are so tiny and may have negative effects on human health and the environment, their removal is a prerequisite. Magnetism, crossflow filtration, and centrifugation are some of the several separation techniques used [110]. Although using nanoparticles to purify water has much potential, there are still some lingering safety concerns.

The processes of synthesis, application, and disposal include the risk of contaminating the environment [110].

4.2.5. Miscellaneous Adsorbents

Tamarindus indica bark was utilized to create bark-based magnetic iron oxide particles (BMIOP), which have been proven to be effective in removing arsenic (As31) from water. The primary benefit of this is the regular magnetic ability to expel As-laden BMIOP [111]. After being heated in the air, new pine wood sawdust-derived magnetically modified hydrochar precursors show better mercury ion removal in water. Using ferric oxide nanoparticles and Indian bale leaves, a magnetic bioadsorbent that can remove arsenic from water was created. It was discovered that a bioadsorbent made from used coffee grounds has a great affinity for chromium(VI) removal [111]. A study suggested the facile synthesis of organosilica-modified Fe_3O_4 (OS/Fe_3O_4) hetero-nanocore and OS/Fe_3O_4@SiO_2 core–shell structure for wastewater treatment. Another study practiced deep eutectic solvent-based microextraction of lead(II) traces from water and aqueous extracts.

4.3. Adsorption by Natural Biomaterials

To manage water resources sustainably, the removal of water pollution caused by inorganic contaminants utilizing low-cost, efficient approaches is an important topic of interest. Bio adsorbents have drawn much interest as an efficient alternative for the removal of inorganic pollutants from water bodies, even though many physical and chemical practices, such as membrane technologies, chemical oxidation, and chemical precipitation, are used for the removal of pollutants [112]. As a result of the limitations and lack of cost-effectiveness of these practices, they cannot be fully implemented. For the removal of heavy metals and dyes from water bodies, numerous naturally occurring low-cost bio adsorbents are being employed, including rice husk, coconut shells, native algae, native fruit peels, leaves, roots, and bark of many native plants, and recycled paper sludge [112].

4.3.1. Rice Husk

Rice husk may effectively remove a considerable proportion of cadmium, copper, zinc, and chromium from water that contains heavy metals. To increase the rate of adsorption, rice husk is treated with hydrochloric acid, tartaric acid, sodium carbonate, or sodium hydroxide [113]. Recently, rice husk ash-based ceramic hollow fiber membranes have been employed to absorb metals from contaminated water [113].

4.3.2. Sugarcane Bagasse (SCB)

Investigations show that lead and cadmium are adsorbed on silica made from SCB. On a pH of 8, activated carbon made from SCB completely absorbs cadmium and zinc. Mercury removal uses versions of SCB that have just recently undergone acid and alkaline treatments. It has been demonstrated that using oxalic acid, citric acid, and NaOH to prepare SCB will adsorb and remove copper ions (Cu21) from water. The removal of fluoride, nitrate, and phosphate ions from water is another use for SCB [114].

4.3.3. Peels of Fruit and Vegetable Paste

Chemical groups, including alkenes, ester, sulfonic acid, amine, and hydroxyl, are present on the peel surface. These functional groups can help in the adsorption process. By treating the material with acids and alkalis, the peel surface can be improved [115]. The adsorption rate of Cu21 increases four times after the physiochemical transformation of pineapple and banana peels. In most investigations, banana peels have been shown to be an effective adsorbent for removing anionic dyes from water. Recent research has shown that an adsorbent made of banana peels is effective in removing fluoride from water [115].

4.4. Membrane Filtration Technologies

High permeated flow, high rejection of contaminants, remarkable longevity, outstanding chemical resistance, and cheap cost are all requirements for a membrane. Inorganic membranes are more expensive, more fragile, and of lower economic value [116]. The primary membrane materials that are utilized commercially are organic polymers. Membrane approaches have the benefits of not requiring chemicals, pH control, little equipment, straightforward automated processes, and reliable water quality. The key restrictions of such techniques are the membrane cost, membrane fouling, and replacement [116].

Two techniques–the microfiltration (MF) and ultrafiltration (UF) separation processes—are driven by low pressure. Although the UF membrane is porous and allows even the coarsest solutes to flow through, the MF membrane has pores that are at least 0.1 microns in size. UF is used in processes including metal recovery. Fouling potential can be decreased using MF as a pretreatment before RO or NF [117]. Nearly all inorganic impurities can be successfully removed from water with RO compounds. The functionalized halloysite nanotubes in a novel polyvinylidene fluoride NF membrane were created with the goal of removing heavy metals efficiently [118]. Multiple metal contaminants in wastewater are treatable with NF and RO. Additionally, increased rejection toward divalent cations as opposed to monovalent cations is demonstrated by NF. Controlling membrane fouling and developing improved membrane materials are major obstacles in membrane operations [118].

4.5. Advanced Oxidation Processes

To remove the contaminants, advanced oxidation processes (AOPs) produce hydroxyl radicals. These radicals are anticipated to effectively interact with wastewater contaminants and make them less hazardous, offering the best wastewater treatment option. AOP acts via the in situ creation of oxidation species and the subsequent interaction of the generated oxidant with the contamination [119]. When compared to other chemical and biological processes, AOPs are more environmentally benign since they do not produce either primary or secondary contamination. In the AOP, which carries out the oxidation of the pollutant, hydroxyl radicals are generated [120].

The process of chemical treatment can be made safer and healthier by producing coagulation factors, ion-exchange materials, or catalysts utilizing biobased materials (Table 2) and naturally occurring minerals. Most wastewater and hazardous solid waste are treated with conventional technologies such as physicochemical and biological methods (Table 1). The new concept of solar nano-ionics has been developed to directly feed solar energy into photocarriers and localized electric fields near the edges of graphene nanostructures that enable effective, mobility-based ion transport with high mass exchange rates and selectivity for water treatment. Photothermal membrane distillation is also another promising technology for desalination and wastewater treatment.

Table 2. Versatile techniques used in inorganic pollutants removal.

S.No.	Techniques	Advantages	Limitations
1	Adsorption	• Simple method • Numerous adsorbents to remove different pollutants • Availability of many commercial adsorbents	• Generate secondary contamination • Regeneration is expensive and ineffective • Adsorbent costs have an impact on treatment costs overall • Most processes are pH-dependent • Pre- and post-treatment are necessary

Table 2. *Cont.*

S.No.	Techniques	Advantages	Limitations
2	Electro-assisted methods	• Insitucoagulant generation • Easy automation	• Energy usage might be a problem, but demand for renewable energy is growing • Scaling and passivation of electrodes • Sludge disposal
3	Membrane filtration	• Minimal area needed • Availability of commercial membranes • No demands for chemicals • High-quality discharge is processed rapidly and effectively	• High investment, repair, and operational costs • Higher energy demands • Membrane obstruction
4	Advanced oxidation processes	• In situ radical synthesis • Reliable for recalcitrant contaminants	• Formation of byproducts • Energy-intensive

5. Toxicity Assessment of Inorganic Pollutants

Wastewater released from the textile dyeing industry has led to disturbance in various environmental factors and causes toxicity to human health. In a study, wastewater samples were collected from the textile dyeing industry before and after physicochemical treatment, and their ecotoxicological assessment was carried out [121]. The toxicity assessment of metals (Hg, Cr, As, Sb, Cd, Sn, Cu, Ni, Mn, Zn, and Pb) was determined on four organisms, namely *Selenastrum capricornutum*, *Vibrio fischeri*, *Daphnia magna*, and *Lepidium sativum*. Metals were quantified using inductively coupled plasma–mass spectrometry (ICP–MS) [121].

The level of toxicity of inorganic elements was investigated in water samples used in greenhouses where artichokes and tomatoes were irrigated [122]. It was observed that different metals were found beyond their required limits as the value of AS^{75} (405 µg/L) was found to be 40 times higher, Ni^{60} (279 µg/L) surpasses the limit by 14 times, Pb^{208} (264 µg/L) and Cd^{111} (351 µg/L) were present 26 times and 70 times more than legal limits, respectively [122].

The concentration level and bioaccumulation of the three most common heavy metals, namely chromium (Cr), cadmium (Cd), and lead (Pb) edible fish, *Channa punctatus*, and in riverine water was investigated in the River Kosi in Rampur in Uttar Pradesh, India [123]. The source of the entrance of these heavy metals into the environment was due to e-waste, industrial activities, municipal urban run-off, coal burning, fertilizers, etc., and indirectly paved the path to contaminants in aquatic systems due to atmospheric deposition and erosions caused by rain. The water of the River Kosi is used for various purposes, including agriculture, domestic uses, and drinking purposes, which increases the concentrations of Cd, Pb, and Cr in seafood consumed by humans. Exposure of aquatic animals to higher levels of heavy metals poses a threat to both fauna and flora. The data revealed the concentrations of Cd, Cr, and Pb in water to be 0.051 ± 0.026, 1.091 ± 0.408, and 0.019 ± 0.002, whereas in the kidneys of *Channa punctatus*, it was found to be 0.076 ± 0.208, 0.482 ± 0.059 and 0.127 ± 0.705, respectively. Exposure to high doses can cause severe diseases such as respiratory irritation, chronic lung disease, and testicular degeneration [123]. There is a dire need to ensure the recycling of discarded materials, which should be properly disposed of.

Heavy metals are persistent and can impact living beings directly or indirectly owing to biomagnifications, as they are not biodegradable and tend to bioaccumulate. Numerous hazardous heavy metal ions can cause cancer and damage various human organs, including the lungs, kidneys, liver, prostate, esophagus, stomach, and skin, even at extremely low concentrations. They can result in causing fatal neurodegenerative disorders and diseases like Alzheimer's and Parkinson's. Metal accumulation in various organs causes oxidative damage, endocrine disruption, and immune system depression. These ill effects of metals can be observed in aquatic species, including phytoplankton, zooplankton, and fish diversity, affecting survival and growth [124].

6. Challenges and Future Perspectives

Due to the non-biodegradable nature of heavy metals, they can quickly accumulate in the surrounding immediate environment [125,126]. Toxic bio-recalcitrant hazardous pollutants are easily released into the environment by various industrial sectors, such as textile, cosmetics, tannery, food, and beverage industries [127]. Organic as well as inorganic contaminants present in various water bodies can have a negative impact on the aquatic ecosystem. Also, extremely acidic wastewater or alkaline might harm aquatic environments. Consuming toxic water poses a serious risk to all life forms. Hence, wastewater must be adequately cleaned before being poured into water bodies [128]. There are various methods for treating hazardous wastes and effluents, including physical, chemical, thermal, biological, and physicochemical methods.

However, the energy-intensive nature of these technologies necessitates high operational and maintenance expenditure [129]. It has been found that chemical treatment is very effective when it comes to hazardous wastes in the form of solid, liquid, and wastewater effluents, but it is inadequate because of the high cost of chemicals used and the generation of secondary waste that must be treated further before disposal. Chlorination is an effective chemical treatment. However, it produces disinfection byproducts (DBPs) [130]. Numerous resistant contaminants can be effectively treated chemically by ozonation. However, this procedure consumes much energy. This approach is expensive due to its poor mineralization effectiveness, preferentially towards contaminants, and insufficient water solubility [131].

When coagulants are used in traditional water treatment methods, a significant quantity of production of silt occurs [132]. To reduce and cure harmful pollutants, using more chemicals is not a sensible strategy for a long-term solution. Also, the Fenton process is efficient in degrading organic pollutants. It produces iron sludge and has a limited pH range. Sustainable treatment is also needed for the secondary waste produced by the Fenton process. Emerging contaminants can be treated using catalyst-based methods, and a variety of homogeneous and heterogeneous catalysts have been created for this purpose. Without an effective system for recovering catalysts, finer catalyst particles may enter effluent streams or end up as solid sludge, both of which can have negative environmental consequences. To decrease secondary waste and lower chemical usage, there is a rising requirement for the development of effective ecological chemical treatment methods.

More emphasis should be given to catalytic synthesis techniques to minimize the toxic effects of customized catalysts [133]. When used in this way, biobased compounds can be used to prepare catalysts [134]—bioremediation—by adopting different metabolic processes that degrade or may transform harmful contaminants into non-harmful forms. Bioremediation has developed from a small-scale technology into a fully established commercialized technology in many industrialized nations, although its rate and extent have varied. It is a robust strategy to use micro-organisms in bioremediation. Nonetheless, the potential of micro-organisms to thrive in a polluted environment is extremely challenging. Biosurfactants and extracellular polymers, which are derived from micro-organisms, can be utilized to remove pollutants from contaminated sites more efficiently [135]. A biosurfactant-based approach to metal bioremediation is an outstanding possibility that is simultaneously ecologically beneficial and manageable. Using biosurfactants to create a metal complex and harness the metal in the soil is a key component of a successful bioremediation design.

Under the green chemistry approach, the harvested metals can also be used to synthesize metal nanoparticles by means of microbes, plant extracts, and biosurfactants. Understanding the molecular unpinning of pollutant degradation and the action of different biosurfactants in the biochemical transformation of both organic as well as inorganic pollutants has been a research area of interest. Furthermore, it is necessary to develop more economical and effective bioremediation models based on biosurfactants. Regardless, the use of these surface-active molecules is sure to enhance and accelerate the elimination of hazardous heavy metals and ensure a clean environment for future generations [136].

Therefore, under the influence of climatic and socioeconomic conditions, controlling freshwater sources is a crucial challenge for authorities. Widespread drinkable water sources in the heart of cities have been depleted because of climate change. On the other hand, it raises the need for water [137]. The existence of significant industrial water-pollution sources demonstrated the adverse effects of power plants on water pollution.

Heavy metal ions are especially concerning among most of the released contaminants because they are frequently discharged. There are eight heavy metals and metalloids whose atomic density is larger than 4 g/cm^3: Copper, cadmium, zinc, lead, mercury, arsenic, silver, chromium, iron, and platinum. A variety of anthropogenic and natural activities are responsible for frequent releases of these harmful metallic elements into the water. The typical quantities of Cr, Mn, Fe, Co, Ni, As, and Cd detected in surface water bodies are noticeably above the maximum permissible limits for drinking water in many locations around the world [138,139]. Figure 5 presents a schematic method for inorganic pollutant removal.

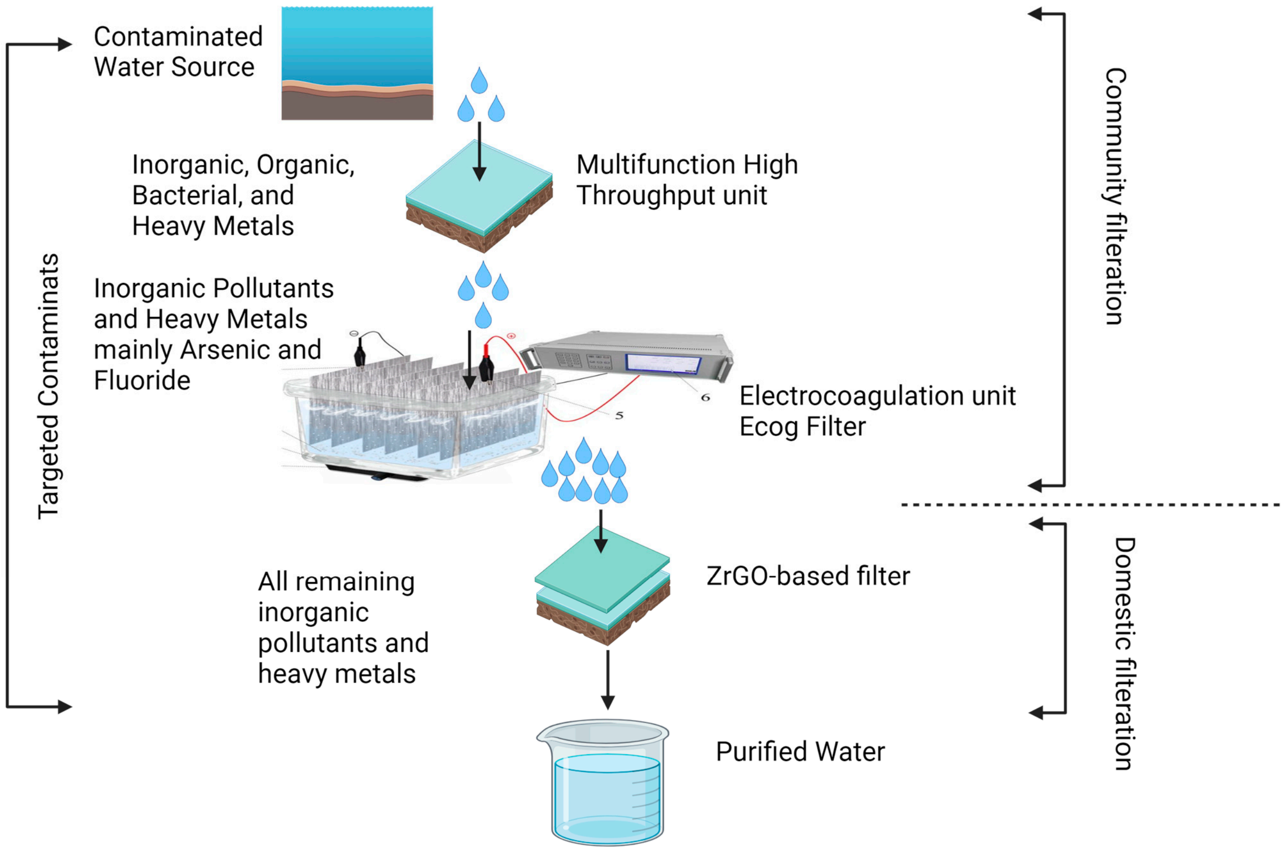

Figure 5. Method for removal of inorganic contaminants from water.

Challenges may be brought on by the financial and maintaining technical constraints for installing and operating that may prevent these technologies from being applied effectively, especially in decentralized settings and developing nations. Therefore, it is necessary to provide solutions that are both efficient and environmentally safe. These solutions could use adsorption techniques that utilize biopolymers or biological or nanotechnology approaches [124,140].

7. Conclusions

Inorganic pollutants are present in the environment in several forms. Water is contaminated by several organic contaminants such as lead, mercury, nitrate, chromium, etc. The identification and quantification of these pollutants can be performed by techniques such as AA, SIFT/MS, ICP–MS, and ICP–OES. The removal of inorganic pollutants from water can be performed using techniques such as electrocoagulation, electrofloatation, adsorption, and membrane filtration technologies. However, each of the removal technologies has its merits and disadvantages. Nonetheless, these technologies play an important role in pollutant removal. Future research should be focused on the cost reduction in clean-up technologies. Waste valorization can be a method for cost reduction of the clean-up products.

Author Contributions: Conceptualization, data curation, methodology, original draft preparation, supervision—V.K.: Original draft preparation—M.S., S.S. (Sonica Sondhiand), K.K., D.S., S.S. (Shivali Sharma) and D.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The corresponding author, Vinay Kumar, is thankful to all the co-authors for their collaborative efforts in writing this paper.

Conflicts of Interest: It is declared that all the authors mutually agree to submit this manuscript to the journal. It is also declared that co-authors do not hold any conflict of interest that may affect the publication of this manuscript.

References

1. El Alouani, M.; Saufi, H.; Moutaoukil, G.; Alehyen, S.; Nematollahi, B.; Belmaghraoui, W.; Taibi, M.H. Application of geopolymers for treatment of water contaminated with organic and inorganic pollutants: State-of-the-art review. *J. Environ. Chem. Eng.* **2021**, *9*, 105095. [CrossRef]
2. Bolisetty, S.; Peydayesh, M.; Mezzenga, R. Sustainable technologies for water purification from heavy metals: Review and analysis. *Chem. Soc. Rev.* **2019**, *48*, 463–487. [CrossRef] [PubMed]
3. Srivastav, A.L.; Ranjan, M. Inorganic water pollutants. In *Inorganic Pollutants in Water*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–15.
4. Patil, S.A.; Shrestha, N.K.; Hussain, S.; Jung, J.; Lee, S.-W.; Bathula, C.; Kadam, A.N.; Im, H.; Kim, H. Catalytic decontamination of organic/inorganic pollutants in water and green H_2 generation using nanoporous SnS_2 micro-flower structured film. *J. Hazard. Mater.* **2021**, *417*, 126105. [CrossRef] [PubMed]
5. Balali-Mood, M.; Naseri, K.; Tahergorabi, Z.; Khazdair, M.R.; Sadeghi, M. Toxic mechanisms of five heavy metals: Mercury, lead, chromium, cadmium, and arsenic. *Front. Pharmacol.* **2021**, *12*, 643972. [CrossRef] [PubMed]
6. Gazwi, H.S.; Yassien, E.E.; Hassan, H.M. Mitigation of lead neurotoxicity by the ethanolic extract of Laurus leaf in rats. *Ecotoxicol. Environ. Saf.* **2020**, *192*, 110297. [CrossRef] [PubMed]
7. Prüss-Ustün, A.; Vickers, C.; Haefliger, P.; Bertollini, R. Knowns and unknowns on burden of disease due to chemicals: A systematic review. *Environ. Health* **2011**, *10*, 9. [CrossRef] [PubMed]
8. WHO. *WHO Human Health Risk Assessment Toolkit: Chemical Hazards*; World Health Organization: Geneva, Switzerland, 2021.
9. Lokuge, K.M.; Smith, W.; Caldwell, B.; Dear, K.; Milton, A.H. The effect of arsenic mitigation interventions on disease burden in Bangladesh. *Environ. Health Perspect.* **2004**, *112*, 1172–1177. [CrossRef]
10. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K.; Sutton, D.J. Heavy metal toxicity and the environment. *Mol. Clin. Environ. Toxicol.* **2012**, *101*, 133–164.
11. Fu, X.; Wang, T.; Wang, S.; Zhang, L.; Cai, S.; Xing, J.; Hao, J. Anthropogenic emissions of hydrogen chloride and fine particulate chloride in China. *Environ. Sci. Technol.* **2018**, *52*, 1644–1654. [CrossRef]
12. Gupta, V.K.; Ali, I.; Saleh, T.A.; Nayak, A.; Agarwal, S. Chemical treatment technologies for waste-water recycling—An overview. *Rsc Adv.* **2012**, *2*, 6380–6388. [CrossRef]
13. Zhang, H.; Bai, Z.; Zhu, L.; Liang, Y.; Fan, X.; Li, J.; Wen, H.; Shi, T.; Zhao, Q.; Wang, Z. Hydrogen sulfide donors: Therapeutic potential in anti-atherosclerosis. *Eur. J. Med. Chem.* **2020**, *205*, 112665. [CrossRef] [PubMed]
14. Goodman, J.E.; Dodge, D.G.; Bailey, L.A. A framework for assessing causality and adverse effects in humans with a case study of sulfur dioxide. *Regul. Toxicol. Pharmacol.* **2010**, *58*, 308–322. [CrossRef] [PubMed]
15. Gholami, F.; Tomas, M.; Gholami, Z.; Vakili, M. Technologies for the nitrogen oxides reduction from flue gas: A review. *Sci. Total Environ.* **2020**, *714*, 136712. [CrossRef]
16. Raub, J.; Benignus, V. Carbon monoxide and the nervous system. *Neurosci. Biobehav. Rev.* **2002**, *26*, 925–940. [CrossRef] [PubMed]

17. Kuttippurath, J.; Singh, A.; Dash, S.; Mallick, N.; Clerbaux, C.; Van Damme, M.; Clarisse, L.; Coheur, P.-F.; Raj, S.; Abbhishek, K. Record high levels of atmospheric ammonia over India: Spatial and temporal analyses. *Sci. Total Environ.* **2020**, *740*, 139986. [CrossRef] [PubMed]
18. Jing, J.L.J.; Yi, T.P.; Bose, R.J.; McCarthy, J.R.; Tharmalingam, N.; Madheswaran, T. Hand sanitizers: A review on formulation aspects, adverse effects, and regulations. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3326. [CrossRef]
19. Dawe, K.E.; Furlani, T.C.; Kowal, S.F.; Kahan, T.F.; VandenBoer, T.C.; Young, C.J. Formation and emission of hydrogen chloride in indoor air. *Indoor Air* **2019**, *29*, 70–78. [CrossRef]
20. Kabir, H.; Gupta, A.K.; Tripathy, S. Fluoride and human health: Systematic appraisal of sources, exposures, metabolism, and toxicity. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 1116–1193. [CrossRef]
21. Adimalla, N.; Qian, H. Groundwater chemistry, distribution and potential health risk appraisal of nitrate enriched groundwater: A case study from the semi-urban region of South India. *Ecotoxicol. Environ. Saf.* **2021**, *207*, 111277. [CrossRef]
22. Fu, Z.; Xi, S. The effects of heavy metals on human metabolism. *Toxicol. Mech. Methods* **2020**, *30*, 167–176. [CrossRef]
23. Budnik, L.T.; Casteleyn, L. Mercury pollution in modern times and its socio-medical consequences. *Sci. Total Environ.* **2019**, *654*, 720–734. [CrossRef]
24. Chasapis, C.T.; Ntoupa, P.-S.A.; Spiliopoulou, C.A.; Stefanidou, M.E. Recent aspects of the effects of zinc on human health. *Arch. Toxicol.* **2020**, *94*, 1443–1460. [CrossRef]
25. Mondal, A.; Nag, S.; Banerjee, P. Coumarin functionalized molecular scaffolds for the effectual detection of hazardous fluoride and cyanide. *Dalton Trans.* **2021**, *50*, 429–451. [CrossRef]
26. Raju, N.J. Arsenic in the geo-environment: A review of sources, geochemical processes, toxicity and removal technologies. *Environ. Res.* **2022**, *203*, 111782. [CrossRef]
27. Alvarez, C.C.; Gómez, M.E.B.; Zavala, A.H. Hexavalent chromium: Regulation and health effects. *J. Trace Elem. Med. Biol.* **2021**, *65*, 126729. [CrossRef] [PubMed]
28. Genchi, G.; Sinicropi, M.S.; Lauria, G.; Carocci, A.; Catalano, A. The effects of cadmium toxicity. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3782. [CrossRef] [PubMed]
29. Taylor, A.A.; Tsuji, J.S.; Garry, M.R.; McArdle, M.E.; Goodfellow, W.L.; Adams, W.J.; Menzie, C.A. Critical review of exposure and effects: Implications for setting regulatory health criteria for ingested copper. *Environ. Manag.* **2020**, *65*, 131–159. [CrossRef] [PubMed]
30. Borah, P.; Kumar, M.; Devi, P. Types of inorganic pollutants: Metals/metalloids, acids, and organic forms. In *Inorganic Pollutants in Water*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 17–31.
31. Pagnin, L.; Calvini, R.; Wiesinger, R.; Schreiner, M. SO_2- and NO_x-initiated atmospheric degradation of polymeric films: Morphological and chemical changes, influence of relative humidity and inorganic pigments. *Microchem. J.* **2021**, *164*, 106087. [CrossRef]
32. Du, X.; Feng, J.; Fang, M.; Ye, X. Sources, influencing factors, and pollution process of inorganic nitrogen in shallow groundwater of a typical agricultural area in Northeast China. *Water* **2020**, *12*, 3292. [CrossRef]
33. Charkiewicz, A.E.; Backstrand, J.R. Lead toxicity and pollution in Poland. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4385. [CrossRef]
34. Liu, S.; Wang, X.; Guo, G.; Yan, Z. Status and environmental management of soil mercury pollution in China: A review. *J. Environ. Manag.* **2021**, *277*, 111442. [CrossRef]
35. Guo, M.; Wang, J.; Du, R.; Liu, Y.; Chi, J.; He, X.; Huang, K.; Luo, Y.; Xu, W. A test strip platform based on a whole-cell microbial biosensor for simultaneous on-site detection of total inorganic mercury pollutants in cosmetics without the need for predigestion. *Biosens. Bioelectron.* **2020**, *150*, 111899. [CrossRef]
36. Van Hien, N.; Valsami-Jones, E.; Vinh, N.C.; Phu, T.T.; Tam, N.T.T.; Lynch, I. Effectiveness of different biochar in aqueous zinc removal: Correlation with physicochemical characteristics. *Bioresour. Technol. Rep.* **2020**, *11*, 100466. [CrossRef]
37. Mamelkina, M.A.; Herraiz-Carboné, M.; Cotillas, S.; Lacasa, E.; Sáez, C.; Tuunila, R.; Sillanpää, M.; Häkkinen, A.; Rodrigo, M.A. Treatment of mining wastewater polluted with cyanide by coagulation processes: A mechanistic study. *Sep. Purif. Technol.* **2020**, *237*, 116345. [CrossRef]
38. Cui, J.; Wang, X.; Yuan, Y.; Guo, X.; Gu, X.; Jian, L. Combined ozone oxidation and biological aerated filter processes for treatment of cyanide containing electroplating wastewater. *Chem. Eng. J.* **2014**, *241*, 184–189. [CrossRef]
39. Pang, D.; Wang, C.-C.; Wang, P.; Liu, W.; Fu, H.; Zhao, C. Superior removal of inorganic and organic arsenic pollutants from water with MIL-88A(Fe) decorated on cotton fibers. *Chemosphere* **2020**, *254*, 126829. [CrossRef] [PubMed]
40. Figoli, A.; Fuoco, I.; Apollaro, C.; Chabane, M.; Mancuso, R.; Gabriele, B.; Rosa, R.D.; Vespasiano, G.; Barca, D.; Criscuoli, A. Arsenic-contaminated groundwaters remediation by nanofiltration. *Sep. Purif. Technol.* **2020**, *238*, 116461. [CrossRef]
41. Bao, Z.; Wang, W.; Wang, X.; Qian, M.; Jin, Y. Sub-chronic difenoconazole exposure induced gut microbiota dysbiosis in mice. *Toxics* **2022**, *10*, 34. [CrossRef] [PubMed]
42. Farooqi, Z.H.; Akram, M.W.; Begum, R.; Wu, W.; Irfan, A. Inorganic nanoparticles for reduction of hexavalent chromium: Physicochemical aspects. *J. Hazard. Mater.* **2021**, *402*, 123535. [CrossRef] [PubMed]
43. Cosio, C.; Renault, D. Effects of cadmium, inorganic mercury and methyl-mercury on the physiology and metabolomic profiles of shoots of the macrophyte *Elodea nuttallii*. *Environ. Pollut.* **2020**, *257*, 113557. [CrossRef] [PubMed]
44. Bashir, S.; Adeel, M.; Gulshan, A.B.; Iqbal, J.; Khan, S.; Rehman, M.; Azeem, M. Effects of organic and inorganic passivators on the immobilization of cadmium in contaminated soils: A review. *Environ. Eng. Sci.* **2019**, *36*, 986–998. [CrossRef]

45. Chellaiah, E.R. Cadmium (heavy metals) bioremediation by Pseudomonas aeruginosa: A minireview. *Appl. Water Sci.* **2018**, *8*, 154. [CrossRef]
46. Haider, F.U.; Liqun, C.; Coulter, J.A.; Cheema, S.A.; Wu, J.; Zhang, R.; Wenjun, M.; Farooq, M. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicol. Environ. Saf.* **2021**, *211*, 111887. [CrossRef] [PubMed]
47. Krstić, V.; Urošević, T.; Pešovski, B. A review on adsorbents for treatment of water and wastewaters containing copper ions. *Chem. Eng. Sci.* **2018**, *192*, 273–287. [CrossRef]
48. Deng, R.; Huang, D.; Wan, J.; Xue, W.; Lei, L.; Wen, X.; Liu, X.; Chen, S.; Yang, Y.; Li, Z. Chloro-phosphate impregnated biochar prepared by co-precipitation for the lead, cadmium and copper synergic scavenging from aqueous solution. *Bioresour. Technol.* **2019**, *293*, 122102. [CrossRef]
49. Pugazhendhi, A.; Ranganathan, K.; Kaliannan, T. Biosorptive removal of copper (II) by Bacillus cereus isolated from contaminated soil of electroplating industry in India. *Water Air Soil Pollut.* **2018**, *229*, 76. [CrossRef]
50. Omeje, K.O.; Ezema, B.O.; Okonkwo, F.; Onyishi, N.C.; Ozioko, J.; Rasaq, W.A.; Sardo, G.; Okpala, C.O.R. Quantification of Heavy Metals and Pesticide Residues in Widely Consumed Nigerian Food Crops Using Atomic Absorption Spectroscopy (AAS) and Gas Chromatography (GC). *Toxins* **2021**, *13*, 870. [CrossRef]
51. Idris, M.G.; Umaru, D.; Aliyu, A.N.; Musa, I.H. Atomic Absorption Spectroscopy Analysis of Heavy metals in water at Daura Gypsum Mining Site, Yobe State, Nigeria. *J. Found. Appl. Phys.* **2022**, *8*, 227–234.
52. Kermani, M.; Jafari, A.J.; Gholami, M.; Shahsavani, A.; Goodarzi, B.; Fanaei, F. Extraction and determination of organic/inorganic pollutants in the ambient air of two cities located in metropolis of Tehran. *Environ. Monit. Assess.* **2022**, *194*, 204. [CrossRef]
53. Akiba, N.; Mancini, R.S.; Carvalho, A.Z.; Gaubeur, I. Determination of Cadmium in Water Samples by Automated Flow-Batch Cloud Point Extraction (CPE) Hyphenated to High-Resolution Continuum Source Flame Atomic Spectrometry (HR-CS FAAS). *Anal. Lett.* **2022**, *55*, 741–754. [CrossRef]
54. Silva, A.S.; Brandão, G.C.; Ferreira, S.L.C.; Santos, A.M.P.D. Sequential and Simultaneous Determination of Cd, Fe and Ni in Toothpastes Employing Slurry Sampling High-Resolution Continuum Source Graphite Furnace Atomic Absorption Spectrometry. *Anal. Lett.* **2022**, *55*, 1192–1206. [CrossRef]
55. Forero-Mendieta, J.R.; Varón-Calderón, J.D.; Varela-Martínez, D.A.; Riaño-Herrera, D.A.; Acosta-Velásquez, R.D.; Benavides-Piracón, J.A. Validation of an Analytical Method for the Determination of Manganese and Lead in Human Hair and Nails Using Graphite Furnace Atomic Absorption Spectrometry. *Separations* **2022**, *9*, 158. [CrossRef]
56. Pacer, E.J.; Palmer, C.D.; Parsons, P.J. Determination of lead in blood by graphite furnace atomic absorption spectrometry with Zeeman background correction: Improving a well-established method to support a lower blood lead reference value for children. *Spectrochim. Acta Part B At. Spectrosc.* **2022**, *190*, 106324. [CrossRef]
57. Gösterişli, T.U.; Cesur, B.; Tezgit, E.; Bakırdere, E.G.; Keyf, S.; Bakırdere, S. Determination of Palladium in Precious Metal Waste by Sieve Conducted Two Syringes Pressurized Liquid Phase Microextraction (SCTS-PLPME) and Slotted Quartz Tube Flame Atomic Absorption Spectrometry (SQT-FAAS). *Anal. Lett.* **2022**, *55*, 175–185. [CrossRef]
58. Serbest, H.; Bakırdere, S.; Keyf, S. Trace Determination of Rhodium in Coating Wastewater by Vortex Assisted Magnetic Nanoparticle Based Solid Phase Microextraction (MNP-SPME) Combined with Slotted Quartz Tube–Flame Atomic Absorption Spectrometry (SQT-FAAS) with Matrix Matching Calibration. *Anal. Lett.* **2022**, *55*, 1672–1684. [CrossRef]
59. Kartoğlu, B.; Tezgit, E.; Yiğit, A.; Zaman, B.T.; Bakırdere, E.G.; Bakırdere, S. Determination of trace nickel after complexation with a schiff base by switchable solvent–liquid phase microextraction (SS-LPME) and flame atomic absorption spectrometry (FAAS). *Anal. Lett.* **2022**, *55*, 1017–1026. [CrossRef]
60. Şaylan, M.; Karlıdağ, N.E.; Toprak, M.; Tekin, Z.; Balçık, U.; Er, E.Ö.; Bakırdere, S. Novel Salicylic Acid Modified Magnetic Nanoparticles Based Ligandless Extraction for the Accurate Determination of Bismuth in Urine Samples by Flame Atomic Absorption Spectrophotometry. *Anal. Lett.* **2022**, *55*, 1719–1730. [CrossRef]
61. Tekin, Z.; Özdoğan, N.; Bakırdere, S. Zirconium nanoparticles based solid phase extraction-slotted quartz tube-flame atomic absorption spectrophotometry for the determination of cadmium in wastewater samples and evaluation of green profile. *Int. J. Environ. Anal. Chem.* **2022**, *102*, 935–944. [CrossRef]
62. Abbasi, F.; Lashari, A.A.; Solangi, I.B.; Baig, J.A.; Kazi, T.G.; Afridi, H.I. Simultaneous quantification of essential and toxic elements from mangoes fruit and its juices. *Int. J. Environ. Anal. Chem.* **2022**, 1–7. [CrossRef]
63. Yağci, Ö.; Akkaya, E.; Bakirdere, S. Nano-sized magnetic Ni particles based dispersive solid-phase extraction of trace Cd before the determination by flame atomic absorption spectrometry with slotted quartz tube: A new, accurate, and sensitive quantification method. *Environ. Monit. Assess.* **2020**, *192*, 583. [CrossRef]
64. Yu, H.; Li, C.; Tian, Y.; Jiang, X. Recent developments in determination and speciation of arsenic in environmental and biological samples by atomic spectrometry. *Microchem. J.* **2020**, *152*, 104312. [CrossRef]
65. Pasetto, L.V.; Richard, R.; Pic, J.-S.; Manero, M.-H.; Violleau, F.; Simon, V. Hydrogen sulphide quantification by SIFT/MS: Highlighting the influence of gas moisture. *Int. J. Environ. Anal. Chem.* **2020**, *100*, 1133–1145. [CrossRef]
66. Chen, W.; Yang, Y.; Fu, K.; Zhang, D.; Wang, Z. Progress in ICP-MS analysis of minerals and heavy metals in traditional medicine. *Front. Pharmacol.* **2022**, *13*, 891273. [CrossRef] [PubMed]
67. Thosago, M.M.; Botha, A.; Ambushe, A.A.; Godeto, T.W. Quantification of Arsenic Species in Wheat Flour Samples by Ion Chromatography Coupled to High Resolution Inductively Coupled Plasma-Mass Spectrometry (IC-HR-ICP-MS). *Anal. Lett.* **2022**, *55*, 2860–2875. [CrossRef]

68. Ahmed, H.A.M.; Alatawi, A.O. Comparison of the ICP OES viewing modes efficiency in the estimation of cadmium (Cd) and lead (Pb) in whole blood samples. *Arab J. Basic Appl. Sci.* **2022**, *29*, 208–214. [CrossRef]
69. Huang, R.; Lv, J.; Chen, J.; Zhu, Y.; Zhu, J.; Wågberg, T.; Hu, G. Three-dimensional porous high boron-nitrogen-doped carbon for the ultrasensitive electrochemical detection of trace heavy metals in food samples. *J. Hazard. Mater.* **2023**, *442*, 130020. [CrossRef]
70. Reid, M.S.; Hoy, K.S.; Schofield, J.R.; Uppal, J.S.; Lin, Y.; Lu, X.; Peng, H.; Le, X.C. Arsenic speciation analysis: A review with an emphasis on chromatographic separations. *TrAC Trends Anal. Chem.* **2020**, *123*, 115770. [CrossRef]
71. Xie, J.; Niu, X.-D.; Xie, J.-J.; He, K.-Q.; Shi, M.-D.; Yu, S.-J.; Yuan, C.-G.; Liu, J.-F. Distribution and chemical speciation of arsenic in different sized atmospheric particulate matters. *J. Environ. Sci.* **2021**, *108*, 1–7. [CrossRef]
72. El Himri, M.; Errasfa, M.; El Kassimi, A.; Naboulsi, A.; El Himri, A.; El Haddad, M. Method validation for arsenic speciation in contaminated soil by HPLC-ICP-MS coupling method. *J. Indian Chem. Soc.* **2022**, *99*, 100684. [CrossRef]
73. Men, X.; Wu, C.-X.; Zhang, X.; Wei, X.; Ye, W.-Q.; Chen, M.-L.; Yang, T.; Xu, Z.-R.; Wang, J.-H. Tracking cellular transformation of As (III) in HepG2 cells by single-cell focusing/capillary electrophoresis coupled to ICP-MS. *Anal. Chim. Acta* **2022**, *1226*, 340268. [CrossRef]
74. D'Amore, T.; Miedico, O.; Pompa, C.; Preite, C.; Nardelli, V. Characterization and quantification of arsenic species in foodstuffs of plant origin: Optimization and validation of a High-Pressure Ion Chromatography and Inductively Coupled Plasma—Mass Spectrometry (HPIC/ICP-MS) method. In Proceedings of the XXVII National Congress of the Società Chimica Italiana (SCI), Online, 14–23 September 2021.
75. Nawrocka, A.; Durkalec, M.; Michalski, M.; Posyniak, A. Simple and reliable determination of total arsenic and its species in seafood by ICP-MS and HPLC-ICP-MS. *Food Chem.* **2022**, *379*, 132045. [CrossRef] [PubMed]
76. KALAYCI, Ş. Investigation of Arsenic Content in Field Pesticides using inductively coupled plasma optical emission spectroscopy (ICP-OES). *Gazi Univ. J. Sci. Part A Eng. Innov.* **2022**, *9*, 96–103. [CrossRef]
77. de Mello, M.L.; Pinheiro, F.C.; Carnaroglio, D.; Nobrega, J.A. Evaluation of Partial digestion as strategy for elemental analysis of inorganic samples by inductively coupled plasma-optical emission spectrometry (ICP-OES)-A proof of concept study. *Anal. Lett.* **2022**, *55*. [CrossRef]
78. Pandey, A.; Manjare, S.; Joshi, A.; Singh, A. Quantification of environmental impact of water pollutants using fuzzy comprehensive model. *Int. J. Environ. Sci. Technol.* **2022**, *20*, 2009–2020. [CrossRef]
79. Kgabi, D.P.; Ambushe, A.A. Quantification and thermo-desorption studies of mercury in sediments from Mokolo River, Limpopo Province, South Africa. *Int. J. Environ. Anal. Chem.* **2022**, 1–14. [CrossRef]
80. Zhang, Y.; Qu, Y.; Zhang, Y.; Gao, Y.; Wang, L. Development of a fluorescent strategy for quantification of fluoride ions in foods and toothpaste. *Chem. Eng. J.* **2022**, *448*, 137631. [CrossRef]
81. Lei, M.; Zhou, J.; Zhou, Y.; Sun, Y.; Ji, Y.; Zeng, Y. Spatial distribution, source apportionment and health risk assessment of inorganic pollutants of surface water and groundwater in the southern margin of Junggar Basin, Xinjiang, China. *J. Environ. Manag.* **2022**, *319*, 115757. [CrossRef]
82. Van Tran, T.; Jalil, A.; Nguyen, D.T.C.; Alhassan, M.; Nabgan, W.; Cao, A.N.T.; Nguyen, T.M.; Vo, D.-V.N. A critical review on the synthesis of NH2-MIL-53 (Al) based materials for detection and removal of hazardous pollutants. *Environ. Res.* **2022**, *216*, 114422. [CrossRef]
83. Bitzer, J.; Heck, S.-L.; Kleist, W. Tailoring the breathing behavior of functionalized MIL-53 (Al, M)-NH2 materials by using the mixed-metal concept. *Microporous Mesoporous Mater.* **2020**, *308*, 110329. [CrossRef]
84. Wu, X.; Yan, R.; Guan, R.; Du, Y.; Liu, Y.; Wu, S.; Zhu, S.; Song, M.; Hang, T. Arsenic-related health risk assessment of realgar-containing NiuHuangJieDu Tablets in healthy volunteers po administration. *Front. Pharmacol.* **2022**, *12*, 761801. [CrossRef]
85. Yang, M.; Li, P.H.; Chen, S.H.; Xiao, X.Y.; Tang, X.H.; Lin, C.H.; Huang, X.J.; Liu, W.Q. Nanometal oxides with special surface physicochemical properties to promote electrochemical detection of heavy metal ions. *Small* **2020**, *16*, 2001035. [CrossRef] [PubMed]
86. Ye, W.; Li, Y.; Wang, J.; Li, B.; Cui, Y.; Yang, Y.; Qian, G. Electrochemical detection of trace heavy metal ions using a Ln-MOF modified glass carbon electrode. *J. Solid State Chem.* **2020**, *281*, 121032. [CrossRef]
87. Theerthagiri, S.; Rajkannu, P.; Kumar, P.S.; Peethambaram, P.; Ayyavu, C.; Rasu, R.; Kannaiyan, D. Electrochemical sensing of copper (II) ion in water using bi-metal oxide framework modified glassy carbon electrode. *Food Chem. Toxicol.* **2022**, *167*, 113313. [CrossRef] [PubMed]
88. Ayala, M.C.; López, L.L.; Jaramillo-Botero, A.; Valencia, D. Electrochemical modified electrode with bismuth film for ultrasensitive determination of aluminum (iii). *J. Electroanal. Chem.* **2022**, *919*, 116552. [CrossRef]
89. Manzoor, A.; Kokab, T.; Nawab, A.; Shah, A.; Siddiqi, H.M.; Iqbal, A. Electrochemical detection of mercuric (ii) ions in aqueous media using glassy carbon electrode modified with synthesized tribenzamides and silver nanoparticles. *RSC Adv.* **2022**, *12*, 1682–1693. [CrossRef]
90. Kaur, R.; Singh, P.; Kaur, N.; Rana, S.; Singhal, S. 2-(Anthracen-9-yl) benzothiazole–modified graphene oxide–nickel ferrite nanocomposite for anodic stripping voltammetric detection of heavy metal ions. *Microchim. Acta* **2022**, *189*, 1–14.
91. Machhindra, L.A.; Yen, Y.-K. A Highly Sensitive Electrochemical Sensor for Cd2+ Detection Based on Prussian Blue-PEDOT-Loaded Laser-Scribed Graphene-Modified Glassy Carbon Electrode. *Chemosensors* **2022**, *10*, 209. [CrossRef]
92. Qiu, Y.; Qu, K. Binary organic-inorganic nanocomposite of polyaniline-MnO2 for non-enzymatic electrochemical detection of environmental pollutant nitrite. *Environ. Res.* **2022**, *214*, 114066. [CrossRef]

93. Katiyar, R.; Rani, K.U.; Sindhu, T.; Jain, H.S.; Ashoka, S.; Channegowda, M. Design and development of electrochemical potentiostat circuit for the sensing of toxic cadmium and lead ions in soil. *Eng. Res. Express* **2021**, *3*, 045026. [CrossRef]
94. Soni, R.; Bhardwaj, S.; Shukla, D.P. Chapter 14—Various water-treatment technologies for inorganic contaminants: Current status and future aspects. In *Inorganic Pollutants in Water*; Devi, P., Singh, P., Kansal, S.K., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 273–295.
95. Sivakumar, R.; Lee, N.Y. Adsorptive removal of organic pollutant methylene blue using polysaccharide-based composite hydrogels. *Chemosphere* **2022**, *286*, 131890. [CrossRef]
96. Tahir, M.B.; Nawaz, T.; Nabi, G.; Sagir, M.; Khan, M.I.; Malik, N. Role of nanophotocatalysts for the treatment of hazardous organic and inorganic pollutants in wastewater. *Int. J. Environ. Anal. Chem.* **2022**, *102*, 491–515. [CrossRef]
97. Saleh, T.A.; Mustaqeem, M.; Khaled, M. Water treatment technologies in removing heavy metal ions from wastewater: A review. Environmental Nanotechnology. *Monit. Manag.* **2022**, *17*, 100617.
98. Li, T.; Xu, H.; Zhang, Y.; Zhang, H.; Hu, X.; Sun, Y.; Gu, X.; Luo, J.; Zhou, D.; Gao, B. Treatment technologies for selenium contaminated water: A critical review. *Environ. Pollut.* **2022**, *299*, 118858. [CrossRef] [PubMed]
99. Koh, K.Y.; Yang, Y.; Chen, J.P. Critical review on lanthanum-based materials used for water purification through adsorption of inorganic contaminants. *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 1773–1823. [CrossRef]
100. Amini, Z.P. Using nanomembrane to heavy metal removal from wastewater: A mini-review. *Adv. Appl. NanoBio-Technol.* **2022**, *3*, 7–13.
101. Shahid, M.K.; Kashif, A.; Fuwad, A.; Choi, Y. Current advances in treatment technologies for removal of emerging contaminants from water–A critical review. *Coord. Chem. Rev.* **2021**, *442*, 213993. [CrossRef]
102. Rajendran, S.; Priya, T.; Khoo, K.S.; Hoang, T.K.; Ng, H.-S.; Munawaroh, H.S.H.; Karaman, C.; Orooji, Y.; Show, P.L. A critical review on various remediation approaches for heavy metal contaminants removal from contaminated soils. *Chemosphere* **2022**, *287*, 132369. [CrossRef]
103. Balakrishnan, R.M.; Uddandarao, P.; Manirethan, V.; Raval, K. Insights on the advanced processes for treatment of inorganic water pollutants. In *Inorganic Pollutants in Water*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 315–336.
104. Paliwal, R.; Rai, J.P.N. Nanomaterials for the Removal of Inorganic Contaminants from Industrial Wastewater. In *Nano-Biotechnology for Waste Water Treatment*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 171–189.
105. Goutam, S.P.; Saxena, G. Biogenic nanoparticles for removal of heavy metals and organic pollutants from water and wastewater: Advances, challenges, and future prospects. *Bioremediat. Environ. Sustain.* **2021**, 623–636. [CrossRef]
106. Baskar, A.V.; Bolan, N.; Hoang, S.A.; Sooriyakumar, P.; Kumar, M.; Singh, L.; Jasemizad, T.; Padhye, L.P.; Singh, G.; Vinu, A. Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: A review. *Sci. Total Environ.* **2022**, *822*, 153555. [CrossRef]
107. Godiya, C.B.; Ruotolo, L.A.M.; Cai, W. Functional biobased hydrogels for the removal of aqueous hazardous pollutants: Current status, challenges, and future perspectives. *J. Mater. Chem. A* **2020**, *8*, 21585–21612. [CrossRef]
108. Chauhan, G.; González-González, R.B.; Iqbal, H.M. Bioremediation and decontamination potentials of metallic nanoparticles loaded nanohybrid matrices–a review. *Environ. Res.* **2022**, *204*, 112407. [CrossRef] [PubMed]
109. Isaeva, V.I.; Vedenyapina, M.D.; Kurmysheva, A.Y.; Weichgrebe, D.; Nair, R.R.; Nguyen, N.P.T.; Kustov, L.M. Modern carbon–based materials for adsorptive removal of organic and inorganic pollutants from water and wastewater. *Molecules* **2021**, *26*, 6628. [CrossRef] [PubMed]
110. Lu, F.; Astruc, D. Nanocatalysts and other nanomaterials for water remediation from organic pollutants. *Coord. Chem. Rev.* **2020**, *408*, 213180. [CrossRef]
111. Duan, H.; Hu, X.; Sun, Z. Magnetic zeolite imidazole framework material-8 as an effective and recyclable adsorbent for removal of ceftazidime from aqueous solution. *J. Hazard. Mater.* **2020**, *384*, 121406. [CrossRef] [PubMed]
112. Wasewar, K.L.; Singh, S.; Kansal, S.K. Process intensification of treatment of inorganic water pollutants. In *Inorganic Pollutants in Water*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 245–271.
113. Ambaye, T.; Vaccari, M.; van Hullebusch, E.D.; Amrane, A.; Rtimi, S. Mechanisms and adsorption capacities of biochar for the removal of organic and inorganic pollutants from industrial wastewater. *Int. J. Environ. Sci. Technol.* **2021**, *18*, 3273–3294. [CrossRef]
114. Saxena, G.; Goutam, S.P.; Mishra, A.; Mulla, S.I.; Bharagava, R.N. Emerging and ecofriendly technologies for the removal of organic and inorganic pollutants from industrial wastewaters. In *Bioremediation of Industrial Waste for Environmental Safety*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 113–126.
115. Gadore, V.; Ahmaruzzaman, M. Tailored fly ash materials: A recent progress of their properties and applications for remediation of organic and inorganic contaminants from water. *J. Water Process Eng.* **2021**, *41*, 101910. [CrossRef]
116. Mortula, M.M.; Abdelrahman, M.; Tatan, B. Comparative Evaluation of Membrane Filtration on the Tertiary Treatment of Synthetic Secondary Effluent. *Separations* **2022**, *9*, 63. [CrossRef]
117. Virga, E.; Field, R.W.; Biesheuvel, P.; de Vos, W.M. Theory of oil fouling for microfiltration and ultrafiltration membranes in produced water treatment. *J. Colloid Interface Sci.* **2022**, *621*, 431–439. [CrossRef]
118. Altmann, T.; Buijs, P.J.; Farinha, A.S.; Borges, V.R.P.; Farhat, N.M.; Vrouwenvelder, J.S.; Das, R. Seawater Reverse Osmosis Performance Decline Caused by Short-Term Elevated Feed Water Temperature. *Membranes* **2022**, *12*, 792. [CrossRef]

119. Brillas, E. A critical review on ibuprofen removal from synthetic waters, natural waters, and real wastewaters by advanced oxidation processes. *Chemosphere* **2022**, *286*, 131849. [CrossRef]
120. Dong, G.; Chen, B.; Liu, B.; Hounjet, L.J.; Cao, Y.; Stoyanov, S.R.; Yang, M.; Zhang, B. Advanced oxidation processes in microreactors for water and wastewater treatment: Development, challenges, and opportunities. *Water Res.* **2022**, *211*, 118047. [CrossRef] [PubMed]
121. Methneni, N.; Morales-González, J.A.; Jaziri, A.; Mansour, H.B.; Fernandez-Serrano, M. Persistent organic and inorganic pollutants in the effluents from the textile dyeing industries: Ecotoxicology appraisal via a battery of biotests. *Environ. Res.* **2021**, *196*, 110956. [CrossRef] [PubMed]
122. Salvo, A.; La Torre, G.L.; Mangano, V.; Casale, K.E.; Bartolomeo, G.; Santini, A.; Granata, T.; Dugo, G. Toxic inorganic pollutants in foods from agricultural producing areas of Southern Italy: Level and risk assessment. *Ecotoxicol. Environ. Saf.* **2018**, *148*, 114–124. [CrossRef] [PubMed]
123. Idrees, N.; Sarah, R.; Tabassum, B.; Abd, E.F. Evaluation of some heavy metals toxicity in Channa punctatus and riverine water of Kosi in Rampur, Uttar Pradesh, India. *Saudi J. Biol. Sci.* **2020**, *27*, 1191–1194. [CrossRef] [PubMed]
124. Kumar, A.; Jigyasu, D.K.; Subrahmanyam, G.; Mondal, R.; Shabnam, A.A.; Cabral-Pinto, M.; Malyan, S.K.; Chaturvedi, A.K.; Gupta, D.K.; Fagodiya, R.K. Nickel in terrestrial biota: Comprehensive review on contamination, toxicity, tolerance and its remediation approaches. *Chemosphere* **2021**, *275*, 129996. [CrossRef]
125. Xu, S.-J.; Shen, Q.; Luo, L.-H.; Tong, Y.-H.; Wu, Y.-Z.; Xu, Z.-L.; Zhang, H.-Z. Surfactants attached thin film composite (TFC) nanofiltration (NF) membrane via intermolecular interaction for heavy metals removal. *J. Membr. Sci.* **2022**, *642*, 119930. [CrossRef]
126. Gholizadeh, M.; Hu, X. Removal of heavy metals from soil with biochar composite: A critical review of the mechanism. *J. Environ. Chem. Eng.* **2021**, *9*, 105830. [CrossRef]
127. Keskin, B.; Ersahin, M.E.; Ozgun, H.; Koyuncu, I. Pilot and full-scale applications of membrane processes for textile wastewater treatment: A critical review. *J. Water Process Eng.* **2021**, *42*, 102172. [CrossRef]
128. Hussein, T.K.; Jasim, N.A. A comparison study between chemical coagulation and electro-coagulation processes for the treatment of wastewater containing reactive blue dye. *Mater. Today Proc.* **2021**, *42*, 1946–1950. [CrossRef]
129. Patel, A.; Arkatkar, A.; Singh, S.; Rabbani, A.; Medina, J.D.S.; Ong, E.S.; Habashy, M.M.; Jadhav, D.A.; Rene, E.R.; Mungray, A.A. Physico-chemical and biological treatment strategies for converting municipal wastewater and its residue to resources. *Chemosphere* **2021**, *282*, 130881. [CrossRef]
130. Song, Z.-M.; Yang, L.-L.; Lu, Y.; Wang, C.; Liang, J.-K.; Du, Y.; Li, X.-Z.; Hu, Q.; Guan, Y.-T.; Wu, Q.-Y. Characterization of the transformation of natural organic matter and disinfection byproducts after chlorination, ultraviolet irradiation and ultraviolet irradiation/chlorination treatment. *Chem. Eng. J.* **2021**, *426*, 131916. [CrossRef]
131. Wang, J.; Chen, H. Catalytic ozonation for water and wastewater treatment: Recent advances and perspective. *Sci. Total Environ.* **2020**, *704*, 135249. [CrossRef] [PubMed]
132. Bouchareb, R.; Derbal, K.; Özay, Y.; Bilici, Z.; Dizge, N. Combined natural/chemical coagulation and membrane filtration for wood processing wastewater treatment. *J. Water Process Eng.* **2020**, *37*, 101521. [CrossRef]
133. Yadav, N.; Garg, V.K.; Chhillar, A.K.; Rana, J.S. Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: A review. *Chemosphere* **2021**, *280*, 130792. [CrossRef] [PubMed]
134. Srivastava, V. Grand Challenges in Chemical Treatment of Hazardous Pollutants. *Front. Environ. Chem.* **2021**, *2*, 792814. [CrossRef]
135. Jabbar, N.M.; Alardhi, S.M.; Mohammed, A.K.; Salih, I.K.; Albayati, T.M. Challenges in the implementation of bioremediation processes in petroleum-contaminated soils: A review. *Environ. Nanotechnol. Monit. Manag.* **2022**, *18*, 100694. [CrossRef]
136. Kumar, M.; Seth, A.; Singh, A.K.; Rajput, M.S.; Sikandar, M. Remediation strategies for heavy metals contaminated ecosystem: A review. *Environ. Sustain. Indic.* **2021**, *12*, 100155. [CrossRef]
137. Fenu, G.; Malloci, F.M. DSS LANDS: A decision support system for agriculture in Sardinia. *HighTech Innov. J.* **2020**, *1*, 129–135. [CrossRef]
138. Pinto, M.C.; Ordens, C.M.; de Melo, M.T.C.; Inácio, M.; Almeida, A.; Pinto, E.; da Silva, E.A.F. An inter-disciplinary approach to evaluate human health risks due to long-term exposure to contaminated groundwater near a chemical complex. *Expo. Health* **2020**, *12*, 199–214. [CrossRef]
139. Prasad, S.; Yadav, K.K.; Kumar, S.; Gupta, N.; Cabral-Pinto, M.M.; Rezania, S.; Radwan, N.; Alam, J. Chromium contamination and effect on environmental health and its remediation: A sustainable approaches. *J. Environ. Manag.* **2021**, *285*, 112174. [CrossRef]
140. Tavker, N.; Yadav, V.K.; Yadav, K.K.; Cabral-Pinto, M.M.; Alam, J.; Shukla, A.K.; Ali, F.A.A.; Alhoshan, M. Removal of cadmium and chromium by mixture of silver nanoparticles and nano-fibrillated cellulose isolated from waste peels of citrus sinensis. *Polymers* **2021**, *13*, 234. [CrossRef] [PubMed]