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"CONTAMINATED WATERS: UNVEILING THE ENVIRONMENTAL AND HEALTH IMPACTS OF GLOBAL WATER POLLUTION"

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Article Info

Abstract

The global water pollution crisis represents one of the most urgent environmental and public health challenges of the 21st century. As industrialization, urbanization, and agricultural practices have intensified, pollution has severely degraded water quality, affecting both surface and groundwater sources. Contaminants such as heavy metals, plastics, agricultural runoff, and untreated wastewater are polluting water bodies worldwide, leading to significant ecological and human health risks. The resulting waterborne diseases, including cholera, dysentery, and typhoid, remain prevalent in many parts of the world, disproportionately affecting vulnerable populations in low-income and developing regions. Additionally, the contamination of drinking water sources has been linked to long-term health problems such as cancer, reproductive disorders, and neurological damage. The environmental impact is equally alarming, with water pollution causing the destruction of aquatic ecosystems, loss of biodiversity, and disruption of the natural water cycle. The degradation of coral reefs, wetlands, and freshwater habitats disrupts ecosystems and food chains, while algal blooms, fueled by nutrient pollution, lead to hypoxic "dead zones" that suffocate marine life. Addressing this crisis requires a multifaceted approach involving stronger regulatory frameworks, investment in water treatment technologies, and increased global cooperation. Furthermore, promoting sustainable agricultural practices, waste management, and pollution control measures will be critical in reducing the influx of contaminants into water bodies. Public awareness and education, combined with innovative solutions, are essential to mitigating the growing water pollution crisis and securing access to clean water for future generations.

Keywords:
Water Pollution, Public Health, Aquatic Ecosystems.

1. Introduction

Water pollution, the release of substances into subsurface groundwater or into lakes, streams, rivers, estuaries, and oceans to the point that the substances interfere with beneficial use of the water or with the natural functioning of ecosystems. In addition to the release of substances, such as chemicals, trash, or microorganisms, water pollution may include the release of energy, in the form of radioactivity or heat, into bodies of water [1].

2. Types of water pollutants

Groundwater pollution occurs when surface pollutants infiltrate underground water bodies. Contamination from fecal matter introduces pathogens such as viruses, protozoa, bacteria, and occasionally helminth eggs, making the water unsafe for drinking and causing diseases like diarrhea and cholera [2]. Nitrate contamination, often from fertilizers, can lead to blue baby syndrome in infants, especially when concentrations exceed 10 mg/L, as seen in rural areas of Bulgaria and Romania. Most nitrates used in agriculture remain in the soil and eventually leach into groundwater, contributing to pollution [3]. Excess fluoride in groundwater causes dental and skeletal issues [4].

In sparsely populated rural areas, pollutants such as fertilizers, pesticides, and eroded soil reach water bodies through runoff during rain or floods [5]. Agricultural runoff leads to eutrophication in freshwater bodies—about half of U.S. lakes are affected. Phosphates promote the growth of cyanobacteria and algae, which deplete dissolved oxygen and release toxins into the food chain. Nitrogen-rich fertilizers also cause oxygen deficiency in aquatic environments, harming marine life. Fertilizer use has been regulated in regions like America and Northwest Europe since 2006, yet their high solubility continues to contribute to leaching and groundwater contamination [6].

Pesticides, particularly water-soluble ones, also contaminate groundwater, with sandy soils increasing leaching rates. Selenium, a naturally occurring heavy metal, accumulates in soil due to irrigation and leaches into water bodies, posing toxicity risks to animals and humans [6].

Airborne pollutants like carbon dioxide, sulfur dioxide, and nitrogen dioxide—originating from fossil fuel combustion, volcanic activity, and industrial processes—react with water to form acids (e.g., sulfuric and nitric acid), contributing further to water pollution. Particulates in the atmosphere also enter water systems through rain [7].

Bad health of population at large is a major hurdle for developing countries toward achievement of productivity and economic growth. The role of health in determining economic growth through affecting total factor productivity is explored by various studies during the last two decades, like Knowles and Owen (1995), Bloom et al. (1999), Gallup and Sachs (2000), Mayer (2001), Bhargava et al. (2001), Webber (2002) and Alvi and Ahmed (2014) along with others. But these studies adopted life. expectancy as an indicator of health which captures mortality only and not the morbidity. WHO (2002) identified that "even though life expectancy has been most commonly used by economists but it does not capture all the aspects of the individual's current health that may affect productive capacity". Cole and Neumayer (2006) adopted the Malnutrition and lack of access to clean water as indicators of poor health. They used data for the period 1965-1995 comprising 52 developing and developed countries (jointly). Due to lack of access to clean water and sanitation, people are suffering from many serious kinds of waterborne diseases like; Diarrhea, typhoid fever, cholera, schistosomiasis, Dengue, Malaria and Hepatitis. According to WHO (2014), diarrheal disease is the primary cause of deaths of almost 1.8 million human population every year (WHO, 2014). According to estimates of Cole and Neumayer (2006), the impact of lack of clean water on world productivity is -0.09 while it is higher for African region, that is, -0.17 [8].

The primary objective of this review is to provide a comprehensive overview of the sources, types, and consequences of global water pollution, with a particular focus on its environmental and public health impacts. While numerous studies have addressed specific pollutants or regional contamination events, there remains a significant research gap in synthesizing this fragmented knowledge into a unified global perspective. Most existing literature tends to isolate chemical, biological, or microplastic pollutants without fully exploring their cumulative and synergistic effects on ecosystems and human health. Furthermore, limited attention has been given to emerging contaminants such as pharmaceuticals, endocrine-disrupting compounds, and antimicrobial-resistant bacteria in water bodies, especially in low- and middle-income countries. This review aims to bridge these gaps by collating recent findings, highlighting under-researched areas, and emphasizing the urgent need for integrated water management strategies and global policy interventions.

2. Sources of water pollution

Water pollution can occur from two sources. 1. Point source and 2. non-point source (Table 1). Point sources of pollution are those which have direct identifiable source. Example includes pipe attached to a factory, oil spill from a tanker, effluents coming out from industries. Point sources of pollution include wastewater effluent (both municipal and industrial) and storm sewer discharge and affect mostly the area near it [9].Whereas non-point sources of pollution are those which arrive from different sources of origin and number of ways by which contaminants enter into groundwater or surface water and arrive in the environment from different non identifiable sources. Examples are runoff from agricultural fields, urban waste etc. Sometimes pollution that enters the environment in one place has effect hundreds or even thousands of miles away. This is known as transboundary pollution [10]. One example is the radioactive waste that travels through the oceans from nuclear reprocessing plants to nearby countries. Water pollutants may be i) Organic and ii) Inorganic water pollutant [11].

2.1. Organic water pollutants: They comprise of insecticides and herbicides, organohalides and other forms of chemicals; bacteria from sewage and livestocks farming; food processing wastes; pathogens; volatile organic compounds etc [12].

2.2. Inorganic water pollutants: They may arise from heavy metals from acid mine drainage; silt from surface run-off, logging, slash and burning practices and land filling; fertilizers from agricultural run-off which include nitrates and phosphates etc. and chemical waste from industrial effluents [13].

Table 1. Characteristics of point and nonpoint sources of chemical inputs to receiving waters [14].

Point Sources	**Nonpoint Sources**
Wastewater effluent (municipal and industrial) - Runoff and leachate from waste disposal sites - Runoff and infiltration from animal feedlots - Runoff from mines, oil fields, unsewered industrial sites - Storm sewer outfalls from cities with a population >100,000 -Overflows of combined storm and sanitary sewers - Runoff from construction sites >2 ha	Runoff from agriculture (including return flow from irrigated agriculture) - Runoff from pasture and range - Urban runoff unsewered and sewered areas with a population. Runoff from construction sites - Runoff from abandoned mines - Atmospheric deposition over a water surface - Activities on land that generate contaminants, such as logging, wetland conversion, construction, and development of land or waterways

3. Industrial wastewater

3.1. Industrial Wastewater

Water with dissolved and suspended substances discharged from various industrial processes, such as the water released during manufacturing, cleaning and other commercial activities, is termed industrial wastewater [15]. The nature of the contaminants present in industrial wastewater depends on the type of the factory and the industry. Examples of industries that produce wastewater are the mining industry, steel/iron production plants, industrial laundries, power plants, oil and gas fracking plants, metal finishers and the food/beverage industry. The various contaminants commonly found in industrial water outlets are chemicals, heavy metals, oils, pesticides, silt, pharmaceuticals and other industrial by-products [16]. In general, it is difficult to treat industrial wastewater, as individual examination of the set-ups and specific treatment plants are required on an industry-based level. Therefore, to deal with this, on-site filter presses are installed to treat the effluent wastewater [17].

Table 2: Industrial sectors and their major water pollutants

Industry	Major water pollutants	Reference
Dye manufacturing	Copper, color, salt, sulfides, formaldehydes	[18]
Textile	iron, chromium, chlorinated compounds, urea, salts, hydrogen peroxide, high pH NaOH, surfactants	[19]
Pharmaceutical	Cadmium, nickel, phenolic compounds	[20]
Plastic	Perfluorooctanoic acid (PFOA), lead, mercury, cadmium, diethylhexyl phthalate	[21]
Agriculture	Fertilizers, pesticides, insecticides	[22]

4. Agricultural wastes

As global food demands rise, agricultural production has intensified, leading to increased use of artificial methods like chemical fertilizers and pesticides. This has significantly contributed to environmental pollution, especially water pollution, which is alarming given that less than 1% of the world's water is freshwater. If polluted, this limited resource can lead to both food insecurity and water scarcity [23]. Agricultural water pollution arises from both point sources (e.g., field runoff, CAFOs) and non-point sources (e.g., pesticide and fertilizer runoff) [24]. Developed and developing nations alike face challenges: in developed countries, point-source pollution from large-scale livestock operations causes eutrophication and ecosystem damage, while in countries like Mexico, pesticide use has contaminated groundwater and surface water [25]. Excessive chemical fertilizer and pesticide use further pollutes water, harming aquatic ecosystems and posing health risks. In countries like India, China, and Bangladesh, lack of regulation and farmer training aggravates the issue. Insecticides such as neonicotinoids disrupt food chains by killing pollinators and leaching into waterways, with widespread ecological consequences [26].

Animal waste from intensive livestock farming in Brazil, Mexico, and China is another major contaminant. Poor waste management leads to leakage and runoff, endangering water quality. Similarly, inefficient irrigation systems, common in India and China, contribute to salinization and water source depletion, while land degradation from erosion adds to sediment pollution [27].

Farmer education is a critical factor; lack of awareness leads to improper chemical and irrigation practices. Moreover, industrial runoff, urbanization, and GMO use further introduce pollutants. Elevated nitrate levels in groundwater particularly in Europe, Asia, and the Americas exceed the WHO safe limit of 50 ppm, raising public health concerns [28].

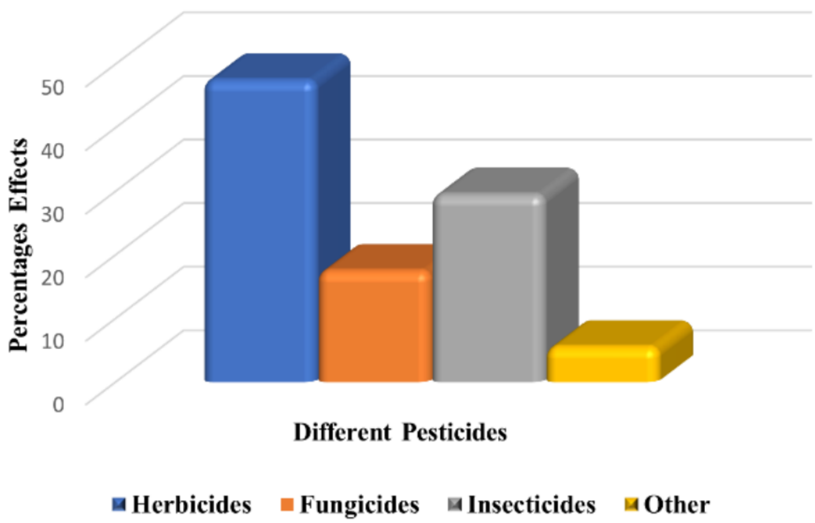

Figure 1. Effects of pesticides used in agriculture [29].

5. Oil spills and marine dumping

Effective disposal of dredged materials requires a strong understanding of environmental factors, including sediment behavior, energy regimes, and the objectives behind dredging and dumping. Predicting the fate of dredged material involves hydrodynamic insights and the use of mathematical models to simulate dredging, transport, and sedimentation processes [30]. Key challenges in dredging include bed sediment disturbance, sediment suspension, and the spread of suspended particles in seawater. Contaminated sediments often contain harmful levels of heavy metals and organic pollutants like copper, chromium, mercury, and PCBs, resulting from years of unregulated pollutant discharge in port areas.

These contaminants can reach significant depths due to mechanical disturbances such as ship anchoring. To manage this, contaminated sediments may be relocated and sealed under clean materials like sand. Offshore oil and gas drilling operations also release pollutants via drilling muds and excavated materials. Despite efforts to minimize their toxicity and enhance biodegradability, drilling waste continues to pose a threat to marine ecosystems especially in tropical and subtropical regions [31]. These operations contribute hydrocarbons to sediments through water flow and biological mixing, sometimes leading to eutrophication and increased biological oxygen demand (BOD). Toxic hydrocarbons can harm biodiversity, though both aerobic and anaerobic microbes may help degrade these substances at the sediment–water interface [32].

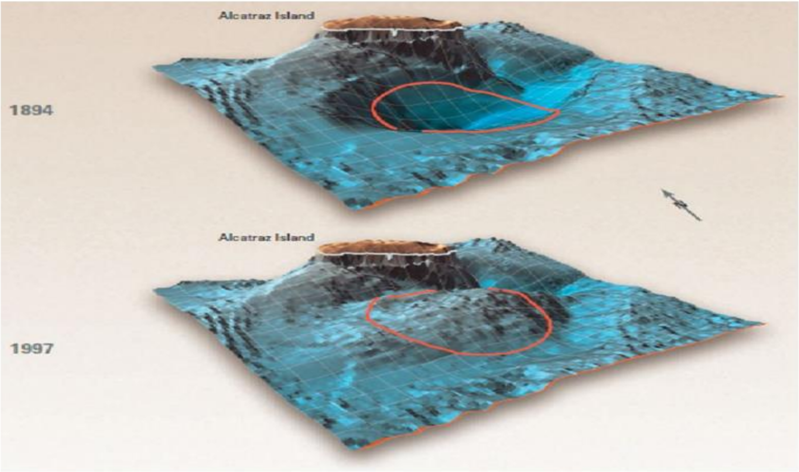

Figure 2: The distribution of dredged materials resulted in the flling of the Alcatraz site between 1894 and 1997 (longterm impact) [33].

6. Emerging contaminants in water

In aquatic systems, colloids (1 nm–1 µm) such as proteins, humic and fulvic acids, peptides, and inorganic materials like manganese oxides and hydrous iron, play a significant role in binding organic and inorganic contaminants due to their high surface area [34]. In freshwater, nanoparticle (NP) aggregates settle into sediments, affecting benthic species, whereas in marine systems, NPs may accumulate between cold and warm currents, posing risks to species like tuna and potentially recycling through biota [35]. Nam et al. observed high TiO_2 NP levels in sediments and showed that NPs can bioaccumulate via food chains and adhere to algal cell walls. The stability, size, and dispersion of engineered nanomaterials (ENMs) influence their transport and bioavailability—large aggregates settle quickly, limiting reactivity, while smaller ones remain more mobile and reactive. Few studies have examined ENM forms in natural waters, though aggregation typical reduces surface area and reactivity [36]. Factors like pH and natural organic matter impact ENM behavior, as noted by Lin et al. [36]. Research continues on the effects of nanomaterials (NMs) on aquatic life, including harmful impacts on trout from TiO_2 NPs. While some fullerenes (e.g., C60, C70) decompose over months, metals and metal oxides are non-biodegradable. Zero-valent iron NPs are used in remediation but lack environmental fate data [37] Avant et al. (2019) used WASP8 to model carbon-based NM exposure (MWCNT, GO, rGO) in four southeastern U.S. aquatic systems, finding long-term sediment retention—up to 37 years in lakes and 1–4 years in rivers. NMs can enter various environmental media through multiple routes.

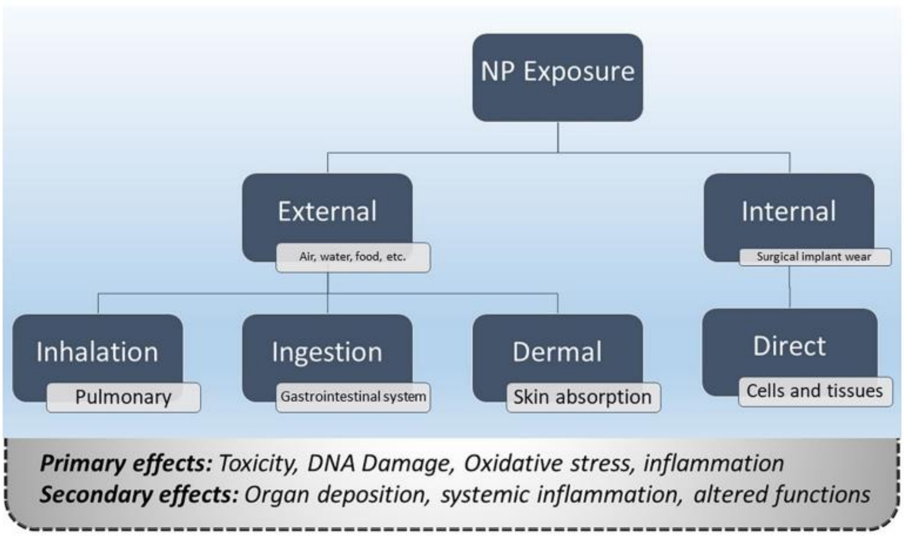

Figure 3: Routes and potential detrimental efects of NP exposure [38].

7. Effect of water pollution

The quality of water deteriorates at every contact made with contaminants hence making the water unsuitable for consumption, usage, or survival. The damage done to the environment by polluted water has a ripple effect in that its impact is felt from the species up to humans that make use of the waste or polluted water [39]. Some of the damage caused by water pollution include but are not limited to the following (Figure 4)

7.1. Stalls economic growth: When the biological oxygen demand which serves as an indicator used in measuring organic pollution in the aquatic system exceeds the allowable limit, it will cause a decline in the gross domestic product of areas within the same water basins by one-third.

7.2. Food chain poisoning: Harvesting of fish in the contaminated water bodies and the use of this water for crop and livestock farming can introduce toxic substances into foods and can cause serious health issues when consumed [40].

7.3. Fading biodiversity: The depletion in water quality caused by pollutants of varying concentrations and sources cannot be overemphasized. It can lead to the uncontrolled spread of phytoplankton in lakes and turn cause fishes to migrate in search of a more conducive environment with moderate growth and spread of phytoplankton.

7.4. Lack of access to clean water: There is constant pressure on the water body as the human population grows uncontrollably, and as such, any source of contamination to the water will deprive so many people the assess to clean water.

7.5. Diseases: The WHO has been able to estimate that almost 2 billion people, due to poverty, are left with no choice but to drink water polluted by both human and animal excreta, thereby exposing them to water-borne diseases, such as dysentery and cholera [41].

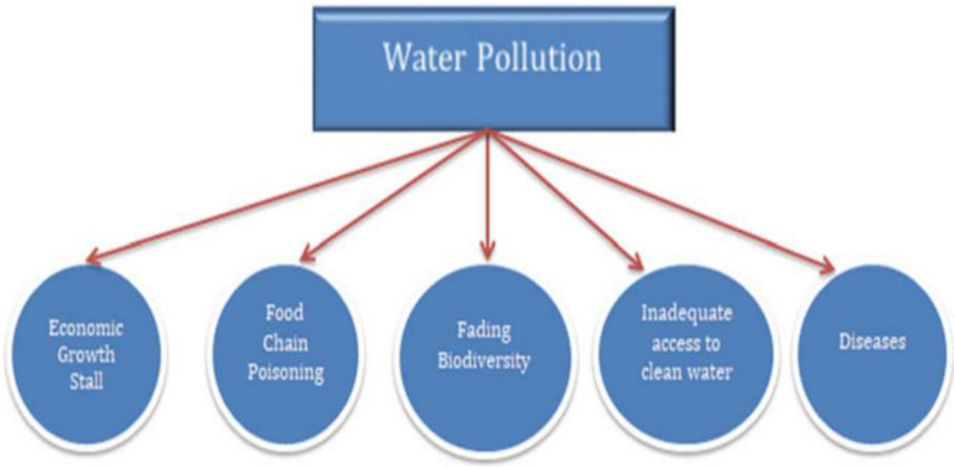

Figure 4: Effects of water pollution

8. Water Pollution and Human Health Risks

In Pakistan, fresh drinking water contamination makes it difficult for people to fnd clean water supplies. Unhealthy water spreads the prevalence of water borne diseases such as hepatitis, cholera, dysentery, cryptosporidiosis, giardiasis, and typhoid [42]. Globally, pathogens are the most serious pollutants in terms of human health. Pathogens can cause diarrhea, cramps, nausea, vomiting, headaches, fatigue, fever, and death. Worldwide 25 million deaths occur due to these water borne diseases per year. The basic hospital information and case studies indicate that most treated diseases are fecal contamination. Almost 25% of patients cured at diferent hospitals, clinics, or healthcare centers sufer from diarrhea, mostly children and adults [43].Subsequently, in Pakistan, most of the health problems reported are caused by direct or indirect contact with polluted water. 45% of child deaths are linked to diarrhea and 60% to overall water borne diseases. Every year in the monsoon season (July–August), due to heavy rainfall, the spread of water borne diseases such as hepatitis, gastroenteritis, typhoid fever, dysentery, E. coli diarrhea, cholera, malaria, rotavirus diarrhea, intestinal worms, and giardiasis will increase. Lack of effective control and prevention measures worsens the situation [44]. In Karachi, renal infection is common due to water pollution, leading to the casualty of 10,000 people yearly [45]. Similarly, in Abbottabad city, contaminated water consumption has been a major cause of dysentery, diarrhea, typhoid, hepatitis, skin infection, and stomach pain. In some regions of Punjab, bone softening and deformation have been reported due to high fluoride content in drinking water (Ahmed et al. 2020b). In Lahore, about 124 children sufered from skeletal fluorosis due to high F^- concentration in drinking water (Khwaja and Aslam 2018). The problem of joint pain, bone deformation, back pain, and spinal defects was traced in Kalalanwala, near Lahore, caused by high fuoride concentration (Farooqi et al. 2007). Microbial contamination, toxic metals (Cd, As, Fe, Ni, and Cr), pesticides, and NO_3^- and F^- are the main threats to water quality [45]. High As contamination in drinking water has been reported in many areas of Pakistan, particularly in Sindh and Punjab provinces. In Badarpur and Ibrahimabad, district Kasur, arsenicosis and dental fuorosis were common in locals due to high As and F^- contamination [46]. It is also reported that in Pakistan arsenic pollution risks more than 50 million people's lives by drinking groundwater. In Bobak village near Manchar Lake Sindh, exposure to the high As concentration over a long period has overwhelming efects on community health. Cancer, skin lesions, discolouration, and cardiac disorders are common [47].In Harnai, Balochistan, a high concentration of NO_3^- in spring water causes blue baby syndrome in infants [48].In Peshawar district, KPK, most drinking water samples were found severely contaminated with Fecal coliform and E. coli bacteria, posing serious health risks to public. The presence of coliform bacteria in drinking water could be contributed to sewage pollution. Acute gastroenteritis was reported in Rawalpindi, Pakistan, in children$\leq$5 years of age. In Karachi, drinking water samples were found heavily contaminated with total coliform and fecal coliform (E. coli), which led to the prevalence of waterborne diseases particularly Diarrhea [49]. In Pakistan, another serious risk to human health is the presence of pesticides in drinking water. Usage of pesticides in agriculture is significantly increasing over the last four decades for crop protection. The migration of pesticides in drinking water has remained a global concern.Headache, dizziness, vomiting, burning of the urinary tract, muscle weakness, skin irritation, and breath shortness led to pesticide exposure have been reported in the country [50].

Figure 5: Agricultural pollutants pose a major threat to the surface water, farms and the health of the people in Sindh. Source (Dawn.com), B Drinking water contaminated in Karachi. Source (thenews.com.pk), C Wastewater pollution in an industrial area of Karachi, and D Untreated effluent flowing into a water drain in Faisalabad. Source [51].

Table 3. Potential health effect of physico-chemical contaminant upon consumed in high levels in drinking water

Contaminant	Potential health risk	Ref
Chlorine	Bladder, colon and rectum cancers in addition to adverse effects on reproduction	[52]
Nitrates and nitrites	Major health problems such as Methemoglobinemia and increase the risk of abortion and even cancers	[53]
Trihalomethanes	Increased risk of bladder cancer	[54]
Sulfate and calcium carbonate	Excessive intake of these element in water may lead to indigestion and severe diarrhea in consumers.	[55]
Heavy metals	Different heavy metals associated with different impact such as toxicity, stability, and carcinogenic and bioaccumulation.	[56]

9. Economical impact of water pollution

Water pollution globally from loads of wastewater discharges amounts to over 5500 billion m3 per year [57].Besides, wastewater reuse is necessary to protect freshwater resources by dumping untreated sewage and using discharged effluents to support plant growth. It also saves water bodies from eutrophication by reducing fertilizer application for plant growth [58].According to Yi et al. (2011), roughly 80% of the freshly extracted water is disposed of as wastewater, yet unexpectedly, 70% of the volume released may be recovered. Among all the uses, one of the key factors contributing to a significant freshwater abstraction is agricultural irrigation, and to deal with the water scarcity issues, the use of treated wastewater can reduce stress on the freshwater sources and hence will prove as a promising technology. Using treated wastewater to irrigate 400 ha of forests in the Moroccan city of Ait Melloul saved 4 Mm3 freshwater yearly, according to Benzine (2012). In Saudi Arabia, 60% of groundwater has been saved while treated wastewater replaced freshwater for irrigation purposes. Wastewater reuse as a source of irrigation water can preserve groundwater and surface water resources from contamination caused by nutrient leaching and runoff induced by mineral fertilizer application. It has the potential to function as a barrier against water contamination caused by wastewater discharges [59].

9.1. Income and expenditures

The reuse of wastewater for agricultural irrigation in Morocco (Tiznit), according to Malki et al. (2017), boosted crop output owing to the fertilizing impact of treated wastewater while also improving farmer income by reducing the usage of fertilizers. Treated wastewater irrigation can increase the welfare of Israel by US $ 3.3 billion [60].Farmers make huge savings on fertilizers because macronutrients (N, P, and K) and micronutrients supplied to crops are freely available from treated sewage. According to Balkhair et al. (2013), fertilizer consumption can be reduced by 94% for alfalfa cultivation and 45% for wheat cultivation, if treated wastewater can be used for irrigation. Vergine et al. (2017) reported savings of about € 280/ha for tomato cultivation using treated wastewater. Other than the cost savings on purchasing fertilizers, farmers earn more due to higher crop yield than the previous sales. Wastewater reuse as irrigation water reduces the stress on freshwater resources. The non-market value is abandoned, even though the contributions from this are not financially compensated. Alcon et al. (2010) estimated that the non-market value might reach as much as € 0.31 per cubic metre of water. It can also exceed the polishing cost of treated wastewater for reuse. Also, wastewater treatment plants (WWTPs) benefit financially from this scheme as energy consumption has been reduced for wastewater treatment [61].In Italy, at Ferrara WWTP, annual pumping costs for wastewater have been reduced significantly. Economic analysis for the reuse wastewater projects discovered that WWTP could significantly lower its pumping cost annually by €200,000.00 due to a reduced effluent volume decrease in conveyance distance by 3 km. The study found that in Italy (Pugalia), treated wastewater, about 97 million m3 /year, could be reused and implemented for irrigation [62]. Although having numerous benefits, adopting wastewater reuse irrigation incurs some extra costs initially to both farmers and WWTP operators. Initially, some money has to invest in the transportation, storage, and polishing of effluent to meet the requirements for reuse. The provision of these investments has an extra burden on farmers and WWTP operators without proper financial support. Higher irrigation costs may increase without proper incentives and adversely affect their income [63].

9.2. Flood and its effects due to water quality

Groundwater, a key part of the natural geological cycle, moves through aquifers and serves as a primary source of drinking water. Floods are a major cause of groundwater contamination, often leading to the spread of waterborne diseases such as cholera, typhoid, and diarrhea due to pathogenic microbes [64]. As a vital component for all life, water becomes hazardous when floods mobilize harmful substances like pesticides, pathogens, and industrial or agricultural chemicals into water bodies, affecting their suitability for human use. Floods significantly impact aquatic ecosystems, disrupting the ecological services they provide. Climate change and shifts in natural water cycles increase flood risks, which can alter river geomorphology affecting the quality and quantity of aquatic life more severely than the floods themselves. These geomorphological changes can displace or destroy aquatic habitats and organisms [65]. Additionally, floods influence freshwater productivity by altering water clarity, oxygen levels, pH, and mobilizing nutrients. Despite these negative impacts, floods also play a constructive role in aquatic ecosystems by enhancing biodiversity and supporting primary productivity, creating habitats that sustain new species [66]. Flooding may harm wildlife and livestock. Large amounts of water may have a detrimental impact on natural, ranching, and farming-related activities. Such extreme flowing water results in the death of thousands of farm animals. Due to a lack of transportation system, these animals cannot be shifted to upper ground areas and are swept away by floodwaters or frightened to death. If a flood is intense and extreme enough, it can result in the loss of habitats and biodiversity in the flooded regions. This will render catastrophic effects on the Ecosystem's biodiversity, habitat potential, and food supply, with long-term consequences for surviving wildlife [67].

9.3. Current Mitigation Strategies and Policy Frameworks

Most existing numerical water Response indicators have emerged from international efforts aimed at evaluating public policy effectiveness, typically within broader frameworks like sustainability or environmental performance. The OECD played a pioneering role by defining 50 Core Environmental Indicators (CEI), including five water-related ones focused on wastewater treatment (OECD 2003), later streamlined into Key Environmental Indicators (KEI) for public and policy use (OECD 2008).The European Environment Agency (EEA) and European Commission (EC) have worked since the mid-1990s to assess EU water policy impacts, producing key indicators such as nitrate concentrations and bathing water quality (Nixon et al. 2003). A core indicator set was formalized in 2004 (EEA 2005), but only one was a water Response indicator. Eurostat's TEPI project defined 60 indicators through expert consultation, again measuring societal response primarily via wastewater treatment [68].Similarly, the World Bank's attempt to create water sustainability indicators in Central America was hindered by poor data (Winograd et al. 1999; Segnestam 2002). The UN has also contributed through efforts like the UNSD/UNEP water questionnaire, capturing two Response indicators on wastewater connectivity. Collaborations such as the Eurostat/OECD Questionnaire (Eurostat 2004) reflect attempts to harmonize global data collection. With the rise of Integrated Water Resources Management (IWRM), new demands emerged for broader indicators. For example, the Mediterranean Strategy for Sustainable Development (MSSD) included six broader Response indicators like water-use efficiency and cost recovery [69].Globally, the UNESCO World Water Assessment Program (WWAP) launched in 2000 and published the World Water Development Reports (WWDP 2003, 2006), reducing initial indicators from 176 to 63. However, Response indicators remain underdeveloped due to data gaps and conceptual challenges. It is increasingly recognized that institutional changes and IWRM implementation are difficult to capture through purely numerical measure. Overall, while traditional indicators focus on wastewater treatment and a few economic measures, broader evaluations of water policy effectiveness especially under IWRM—require qualitative approaches, as many critical factors are not easily quantifiable [70].

10. General methods for wastewater treatment

When water is polluted and decontamination becomes necessary, the best purification approach should be chosen to reach the decontamination objectives (as established by legislation). A purification process generally consists of five successive steps as described in Figure 6 preliminary treatment or pre-treatment (physical and mechanical); (2) primary treatment (physicochemical and chemical); (3) secondary treatment or purification (chemical & biological); (4) tertiary or final treatment (physical and chemical); and (5) treatment of the sludge formed (supervised tipping, recycling or incineration). In general, the first two steps are gathered under the notion of pre-treatment or preliminary step, depending on the situation [71]. Pre-treatment consists of eliminating the (floating) solid particles and all suspended substances from the effluent. This pre-treatment stage, which can be carried out using mechanical or physical means is indispensable, before envisaging secondary treatment because particulate pollution (e.g. SS, colloids, fats, etc.) will hinder later treatment, make it less efficient or damage the decontamination equipment. Primary chemical treatment such as oxidation for cyanide destruction and Cr (VI) reduction, pH adjustment, pre-reduction of a high organic load may also be required. For instance, effluent from paper mills contains abundant SS such as fibers, fillers and other solids [72]. Effluents from textile mills have a very variable pH although it is often alkaline, containing a high organic load. It is therefore indispensable to pre-treat these effluents before considering secondary treatment. However, these treatments alone are, in many cases, incapable of meeting the legislation requirements. Before its discharge into the environment or its reuse, the pre-treated effluent must undergo secondary purification treatment using the most appropriate of the biological, physical or chemical techniques available to remove the chemical pollution. In certain cases, a final or tertiary treatment (step 4 in Figure 6) can also be required to remove the remaining pollutants or the molecules produced during the secondary purification (e.g. the removal of salts produced by the mineralization of organic matter). However, the use of tertiary treatment in Europe is limited, though it may be necessary in the future if new restrictions are applied. The main tertiary treatments employed to date at a few industrial sites are adsorption using activated carbons (AC), ion-exchange, membrane filtration (ultrafiltration, reverse osmosis), advanced oxidation, and constructed wetlands (CW). In Europe, most of the CW are applied for domestic sewage and municipal wastewater treatment. However, the diversity of CW configurations makes them versatile for implementation to treat industrial effluents (e.g. tannery wastewater, pulp and paper post-treated effluents) [73].

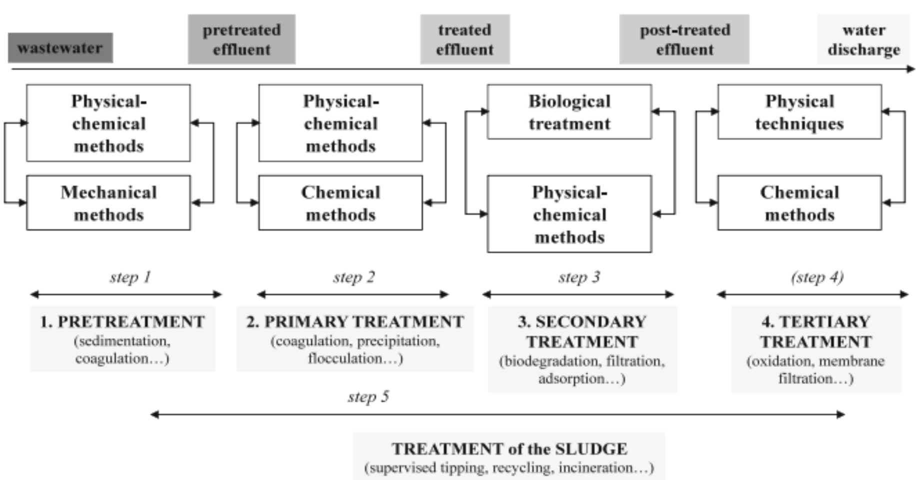

Figure 6: Overview of the main processes for the decontamination of contaminated industrial wastewaters

10.1. Technologies Available for Contaminant Removal

In general, conventional wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids including colloids, organic matter, nutrients, soluble contaminants (metals, organics...) etc. from effluents. A multitude of techniques classified in conventional methods, established recovery processes and emerging removal methods can be used (figure 7) [74].

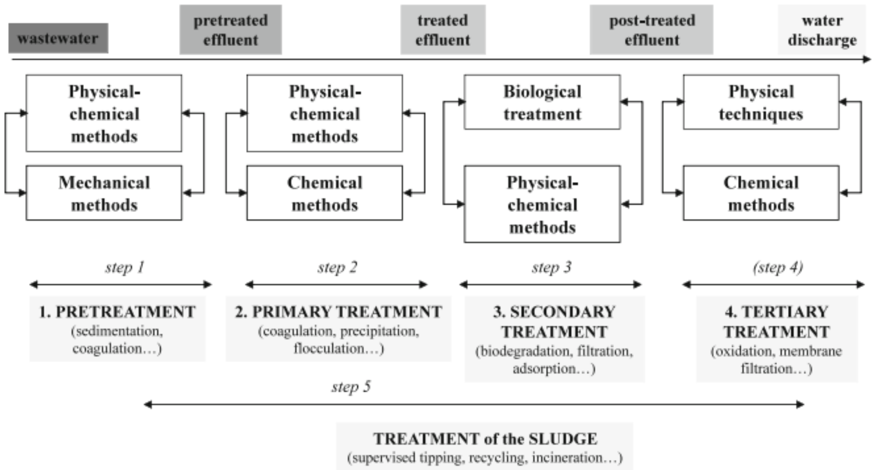

Figure 7: Overview of the main processes for the decontamination of contaminated industrial wastewaters [72].

11. Conclusion and Future perspective

Global water pollution continues to be a critical threat to both environmental integrity and human health, with contaminated waters resulting from industrial discharges, agricultural runoff, and poor sanitation infrastructure. These pollutants contribute to the spread of waterborne diseases, degrade aquatic ecosystems, reduce biodiversity, and impose substantial economic burdens, particularly in developing regions. Although international efforts have led to the development of various monitoring indicators, most remain limited in scope and fail to capture the full complexity of water management and societal responses. Looking ahead, an integrated and holistic approach is essential to address these challenges. Strengthening Integrated Water Resources Management (IWRM) through the inclusion of both quantitative and qualitative indicators can offer a more comprehensive understanding of policy effectiveness. Advancing data collection systems and fostering global cooperation will be crucial to overcoming current information gaps, especially in resource-limited settings. Investments in modern wastewater treatment facilities, particularly in rapidly urbanizing areas, will help mitigate pollution at its source. The adoption of innovative technologies—such as biosensors, real-time monitoring systems, and nature-based solutions—can enhance detection and prevention of contamination. Furthermore, raising public awareness and encouraging community participation can foster behavioral change and improve water stewardship. Aligning water pollution control efforts with climate change adaptation strategies will also be vital to building resilient ecosystems and protecting human well-being. With coordinated global action and equitable implementation, it is possible to reduce the adverse impacts of contaminated waters and ensure safe, sustainable water access for future generations.

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