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The Role of Wastewater Recycling in Sustainable Water Management: A Review

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Abstract

Sustainable water management relies on the recycling of wastewater, which offers a practical solution to address the growing demand for fresh water due to increasing populations and climate changes. This review examines how wastewater recycling plays a role in encouraging water conservation, reducing environmental pollution, and enhancing resource recovery. It looks into various advanced treatment methods—like membrane filtration, biological processes, and chemical treatments—that enable safe reuse of wastewater for both nondrinking and drinking purposes. The article emphasizes the benefits of wastewater recycling, which include decreased reliance on fresh water sources, lower energy use, and recovery of nutrients, highlighting environmental, economic, and social gains. This review underscores the significance of wastewater recycling as a key strategy for achieving sustainable water management and ensuring long-term water availability in rural and urban settings.

Keywords: Wastewater, Recycling, Sustainability, Water Management, Fresh water

1. OVERVIEW OF WATER

Water serves as a universal solvent and is a clear, nearly colorless substance that plays a crucial role in Earth's rivers, seas, lakes, and oceans, fulfilling a fundamental requirement for most living beings. Its chemical representation is H_2O (Azad & Hassan, 2020). This formula indicates that there are two hydrogen atoms and one oxygen atom bonding together via a covalent connection. Covering approximately 72 percent of the Earth's surface, water is an essential solvent, providing a necessary resource across various forms of life, including animals, birds, and humans (Osarugue *et al.*, 2020). About 96. 5 percent of the Earth's crust is found in oceans and seas. Groundwater makes up only 1. 7 percent, with another 1. 7 percent located in glaciers and icecaps in Antarctica and Greenland. A tiny fraction, about 0. 001 percent, exists as vapor, clouds, and precipitation (Hoa & Hue, 2018). Only 2. 5 percent of all water is freshwater, while 98. 8 percent of the surface water is contained in ice and groundwater. Less than 0. 3 percent of freshwater is accessible in rivers, lakes, and the atmosphere, with even smaller quantities found within biological items like toilets, restrooms, kitchens, chimneys, mattresses, and products from various chemical and leather industries. The water circulating on Earth continually moves in and out through the water cycle (Bichi, 2013).

Untreated water carries various suspended solids and dissolved materials that must be eliminated during the purification process, as they contribute to the water's turbidity and discoloration (Aho & Agunwamba, 2014). The elimination of these particles is achieved using traditional coagulating agents such as metal salts including aluminum sulfate, ferric chloride, and ferrous sulfate. However, it's essential to regulate the use of aluminum salts since they can leave residual aluminum in the treated water, potentially causing health issues by significantly impacting the central nervous system and resulting in negative neurological effects, particularly in cases like Alzheimer's disease (Ravikumar & Udayakumar, 2020). Additional research has suggested that such residues could pose carcinogenic risks (Aziz *et al*., 2020).

Water is typically examined from either a physical or normative standpoint. From a physical viewpoint, conversations tend to concentrate solely on the land aspect of the hydraulic cycle, which includes blue water, green water, and gray water1. A significant portion of the conversation emphasizes blue water, which distinguishes between surface water and groundwater. Consequently, most discussions revolve around less than 3% of the overall water. Blue water includes all liquid water produced from runoff found in rivers, lakes, and aquifers. Green water refers to precipitation that converts to soil moisture and subsequently returns to the atmosphere through evapotranspiration (Falkenmark and Rockstrom (2006) provide further insight into these relationships). Gray water is defined as water that has been degraded through human activities. This is a component of the hydrosphere (Shiklomanov, 1993). Although these dialogues contain technical jargon, they represent more profound societal matters related to values and norms. Therefore, it is not surprising that varying stakeholders hold distinct perspectives on water (Linton, 2010). Numerous individuals see water as a natural resource (Falkenmark & Lindh, 1974; Clarke, 1993; Glieck, 1993; Postel, 1997). Alternatively, some (mainly economists) contend that it ought to be regarded as a commodity or a production factor (Winpenny, 1994; Rogers *et al*., 2002). Regardless, water is fundamentally a life source. Therefore, it has been suggested that water should be deemed a basic need, thus constituting a right that individuals should have access to (Glieck, 1998). Advocates of ecocentric views have indicated that similar rights should also be provided to other species (Merchant, 1997; Breckenbridge, 2005).

These different normative perspectives on water lead to practical consequences, as each corresponds to a separate management strategy. As a result, the often contentious debates among these viewpoints are closely linked with disputes regarding specific policy actions (Bakker, 2007). A shared aspect in these normative debates is the understanding of water as a singular entity. In other words, participants refer to all water (usually blue) simply as 'water'. However, this understanding has not always prevailed. The notion of water as a single entity, based on its chemical makeup, is a more recent perspective (Linton, 2010). Historically, people viewed water in plural terms, as 'waters', which encompassed various wet and cool substances like slight water, standing water, clear water, etc. (Hamlin, 2000). While it is acknowledged that water has a unified chemical makeup, one can question whether all substances made of H_2O should be regarded in the same manner. Water is essential for human existence. This widely accepted truth underlies the developing standpoint that fundamental human water requirements are a human right (Glieck, 1998; Cunha, 2009). However, human rights extend beyond mere survival.

2. ESSENCE OF WASTEWATER TREATMENT AND REUSE

All significant landbased living organisms, ecosystems, and humans rely on freshwater (defined as water containing less than 100 mg L^{-1} of salts) for survival. The predominant type of water on Earth is saline, making up around 97% of it. Of the remaining 3% of water, approximately 87% is trapped in glaciers and polar ice caps. This means that just 0. 4% of all water on our planet can be considered accessible freshwater. This accessible freshwater is a renewable resource, but its natural replenishment is limited by the water cycle. Unfortunately, the distribution of freshwater resources is not uniform worldwide. In areas where significant rainfall occurs, storage challenges often arise due to limited space. Additionally, the freshwater available needs to be shared between natural ecosystems and human usage. Human needs encompass more than just drinking; they also include water for agriculture, urban areas, and industries. Shortages of freshwater can heighten the chances of conflict, cause public health issues, lower food production, restrict industrial growth, and create environmental threats.

However, the issues related to freshwater shortages stem not only from uneven availability and increasing demand but also from the deteriorating quality of already utilized freshwater sources. This decrease in water quality is mainly caused by pollution. It is essential to recognize that the broader context of water resources includes the marine environment. Historically, this was linked mostly to fishing resources, but today it also involves tourism and sources for desalination. Untreated wastewater from industries introduces harmful substances into both freshwater and saline water bodies. These affected areas include ponds, lakes, rivers, coastal regions, and oceans. It is important to remember that pollutants released into rivers or other freshwater environments ultimately flow into the sea, which serves as the final destination for waterborne contaminants if they are allowed to move through the ecosystem without barriers. An example of this kind of pollution can be seen in the rivers that run through cities and industrial zones, such as Hanoi and Ho Chi Minh City in Vietnam, where they collect harmful materials like heavy metals and organochlorine pesticides and herbicides.

These contaminants eventually make their way to the ocean, posing risks to fishing industries (Nguyen *et al.*, 1995). For instance, on Hainan Island in Southern China, various industries, including sugar factories, paper production facilities, shipyards, and fertilizer manufacturing, were responsible for nearly half of all wastewater that reached the ocean. This situation led to occurrences of red tide in Houshui Bay, as well as in a region northwest of the island (Du, 1995). It is clear that industrial wastewaters that are not properly treated and are released into rivers will influence not just the freshwater in those areas but also the coastal waters and seas. Eventually, marine resources, including mangroves, reefs, and fisheries, will suffer. Thus, the release of improperly treated industrial effluents can have extensive repercussions. In recent years, industrial pollution has become increasingly recognized as a prominent issue in coastal regions of Southern China, Vietnam, Kampuchea, and Thailand. The impacts of these pollutants on water ecosystems can be categorized into a few key areas:

(a) Physical effects — This encompasses changes in water clarity and disruptions to oxygen levels in the water. Turbidity influences water clarity, which may stem from inorganic (Fixed Suspended

Solids or FSS) and/or organic materials floating in the water (Volatile Suspended Solids or VSS). The latter can decompose, leading to oxidation issues as well. Increased turbidity obstructs light penetration, which in turn hampers photosynthesis. Additionally, the resultant clarity loss can negatively impact aquatic creatures' ability to find food since they may struggle to see their prey. Minute particulates can also block fish gills, hindering their breathing and potentially leading to death. Settling particulates could accumulate on plant leaves and the bottoms of water bodies, creating sludge layers that may eventually suffocate benthic organisms.

As layers of sludge build up, they can eventually transform into sludge banks. If these banks contain organic materials, the breakdown process can lead to unpleasant smells. On the other hand, lighter particles than water tend to float and create a layer of scum on the top. This scum layer blocks light and prevents oxygen from dissolving. Due to this blockage, photosynthesis is negatively impacted. Typically, there are limits set for Total Suspended Solids in wastewater or processed wastewater, such as 30 mg L^{-1} or 50 mg L^{-1}. A lot of industrial wastewaters include oil and grease (O&G). While some of this may be organic, many consist of mineral oils. Regardless of whether they are organic or mineral, both types disrupt the air-water interface and limit oxygen transfer. In addition to hindering oxygen movement from the air to the water, O&G—especially mineral oils—can create further problems. Unlike residential sewage, industrial wastewater often comes at temperatures much higher than the surrounding environment. This increase can elevate the temperature of the receiving water, which decreases oxygen solubility. Additionally, sudden temperature shifts can cause thermal shock, which might be harmful or fatal to sensitive species. However, heat does not always negatively affect organisms since it can enhance growth rates; still, this can lead to a situation where certain species thrive more than others, ultimately harming biodiversity over time.

(b) Oxygen depletion and oxidation — As mentioned earlier, aquatic environments can naturally enrich themselves with oxygen through atmospheric absorption and the photosynthesis carried out by aquatic vegetation. Algae, in particular, play a significant part in this process. Nonetheless, there is a limit to how much oxygen can be restored. If the oxygen levels drop due to biological or chemical reactions caused by organic or inorganic materials that demand oxygen (as indicated by BOD or COD), the dissolved oxygen (DO) levels will fall. This decrease can become severe enough to create septic conditions. One sign of these conditions is unpleasant odors that arise from anaerobic and facultative organisms. An instance of this is when facultative bacteria reduce compounds with bonded oxygen like sulphates, leading to the emission of hydrogen sulphide. The reduction of free oxygen could threaten the survival of aerobic species. However, DO levels do not need to reach zero for there to be negative impacts. A drop to 3–4mg L^{-1} could still be detrimental to larger organisms like certain fish species, despite the water still having a considerable amount of oxygen. If there are also harmful substances present, the DO threshold for adverse effects could be even higher. Meanwhile, high water temperatures from warm effluents present a distinct situation. Increased temperatures might enhance metabolic rates (potentially doubling with each 10°C increase) but simultaneously decrease the amount of oxygen that can dissolve in water. This creates a situation where demand for oxygen rises even as its supply diminishes. Given the influence of DO levels on aquatic life, assessing the BOD for any discharge is deemed crucial. Common BOD_5 limits are typically set at levels like 20 and 50mg L^{-1}.

(c) Toxicity or inhibition and persistence — Such impacts can result from either organic or inorganic compounds and may be either short term or long term. Examples include the pesticides and heavy metals previously mentioned. A considerable amount of industrial wastewater includes these potentially harmful or toxic elements. The presence of these substances in an ecosystem may create biases. The community's population tends to favor members that show greater tolerance to various substances, leading to the elimination of those that are less tolerant and a subsequent decline in biodiversity. Similarly, understanding how these substances affect biological systems is crucial not just for environmental protection but also for their influence on the biological systems employed in treating industrial wastewater. Even if the treatment of such wastewater seems effective, this does not guarantee that the quality of water in a nearby body will remain unchanged. For instance, small traces of residual phenol in water can interact with chlorine during the treatment process for drinking water, which can produce chlorophenols. These can create unpleasant tastes and odors in the finished water. Besides the organic pollutants that could be harmful or toxic, there are also those that resist biological breakdown. These persistent substances can accumulate in living organisms, leading to concentrations in their tissues that are much higher than those found in the surrounding environment, making them unsuitable as food for higher level predators, including humans. While some organic compounds may resist breakdown, metals essentially do not degrade in the environment.

(d) Eutrophication—When compounds containing nitrogen and phosphorus enter water bodies, they can change the water's fertility. This increased fertility may lead to an overabundance of plant growth, which can include the growth of algae. Such growth can have various effects on the water, like making it murkier, reducing oxygen levels, and causing toxicity. In clean water bodies, algal growth is often restricted due to a lack of nutrients. Nutrients consist of larger ones like nitrogen, phosphorus, and carbon, as well as smaller ones like cobalt, manganese, calcium, potassium, magnesium, copper, and iron, which are needed only in tiny amounts. Concerns about eutrophication primarily focus on phosphorus and nitrogen, because the levels of other nutrients in nature are typically sufficient. In freshwater systems, phosphorus is usually the nutrient that limits growth, whereas nitrogen tends to be limiting in estuarine and marine environments. Therefore, when treating industrial wastewater or domestic sewage, efforts can be made to remove either phosphorus or nitrogen based on the specific water body, to maintain the nutrient limiting condition. Given the coastal characteristics of many Asian countries, it is likely that nitrogen removal would be essential if the wastewater had high amounts. If the water body no longer has a nutrient limitation, and conditions such as temperature are suitable, excessive algae or algal blooms (like red tides) may result. Besides causing visual concerns, these algal blooms can impact the local fishing productivity. It’s important to recognize that not all industrial wastewater has high levels of nutrients, whether macro or micro. If there is a shortage of nutrients, it can lead to process instability or the growth of unwanted microorganisms during the biological treatment of the wastewater. Bulking sludge is one indicator of this issue. To solve this nutrient shortfall, supplementation is necessary. The amounts added should be monitored closely to prevent creating a situation with excessive nutrients, which could end up in the treated effluent. For biological treatment, the ideal ratio of BOD to nitrogen to phosphorus is often considered to be 100:5:1, while the minimal acceptable ratio is typically 150:5:1.

3. WATER TREATMENT METHODS

Water soaking into the soil and underground layers creates groundwater, and its final makeup is influenced by particular geological structures as well as the duration the water remains in those areas (Hodge, 2018). The flow of groundwater is controlled by how easily it can move through layers that hold water. For example, clay layers restrict water movement due to their low permeability, while sand or chalk layers allow water to flow easily because they have high permeability. Groundwater is categorized based on the main elements present, which include cations and anions, uncharged particles, trace substances, gases such as CO_2 and O_2, organic materials, and humanmade substances like pesticides and solvents (Hodge, 2018). The initial procedures fall under the first stage of treatment before the water undergoes additional processing.

3.1 Screening

This stage involves getting rid of large floating items and other debris from the water. Different types of screens employed in this process include manual bars, mechanical bars, drum screens, band screens, disc screens, and passive well screens.

3.2 Coagulation

In this initial step, the charges on particles are destabilized. Coagulants with opposite charges to those on the suspended particles are introduced to the water to counteract the negative charges on tiny, non-settling solids. The choice of coagulant is determined by the characteristics of the suspended particles needing removal, the conditions of the raw water, the design of the treatment facility, and the expenses related to the necessary chemicals (Harris, 2007; Joone, 2010).

3.3 Flocculation

During flocculation, a gentle mixing process, the size of particles increases from very tiny microflocs to larger, visible particles. This slow mixing brings microflocs together, causing them to collide and merge, forming larger clumps called pinflocs. The size of the flocs keeps increasing through further collisions and interactions with inorganic polymers from the coagulant or organic polymers added. This process generally takes around 20 to 45 minutes (Kumar and Awasthi, 2009).

3.4 Sedimentation

Conventional treatment facilities use sedimentation basins. In contrast, direct filtration systems bypass the sedimentation phase and move straight into filtration. The sedimentation detention time typically varies from 1 to 4 hours (Shuler and Kargi, 2002; Benje, 1976).

3.5 Filtration

This is the concluding phase for removing suspended material. The method involves allowing water to flow through a layer of material to filter out impurities. Although a sand filter is usually adequate in lowering target parameter concentrations, a BAC filter significantly enhances water quality. The slow sand filter efficiently reduces concentrations of iron and arsenic, while the BAC filter effectively decreases the DOC to under 1 mg/L. Together, these filters help lower color and turbidity (Mallevialle *et al*., 1996; Tebbutt, 1997).

3.6 Slow Rate Gravity Filtration

This method features low filtering speeds ranging from 45 to 150 gallons per day per square foot (0. 03 to 0. 10 gallons per minute per square foot), utilizing a 24 to 30inch deep bed of silica sand as the filter media (Huisman and Wood, 1974).

3.7 Rapid Rate Gravity Filtration

In rapid filtration, sand is often the material used for filtering, but this method greatly differs from slow sand filtration. This difference arises because coarser sand is employed, with grain sizes that typically range from 0. 4 to 1. 2 mm, and the rate of filtration is much faster, usually falling between 5 and 15 m3/m2. h (120360 m3/m2. day) (Ives, 1970; Elberling 2002).

3.8 Bioreactors

For more than a century, bioreactors have effectively played a role in treating wastewater. The processes involving bioreactors can be classified based on how biomass is retained. Biomass can either develop on a substrate in a fixed growth form, such as biofilm systems, or exist as a suspension in sludge processes (Langwaldt and Puhakka, 2000).

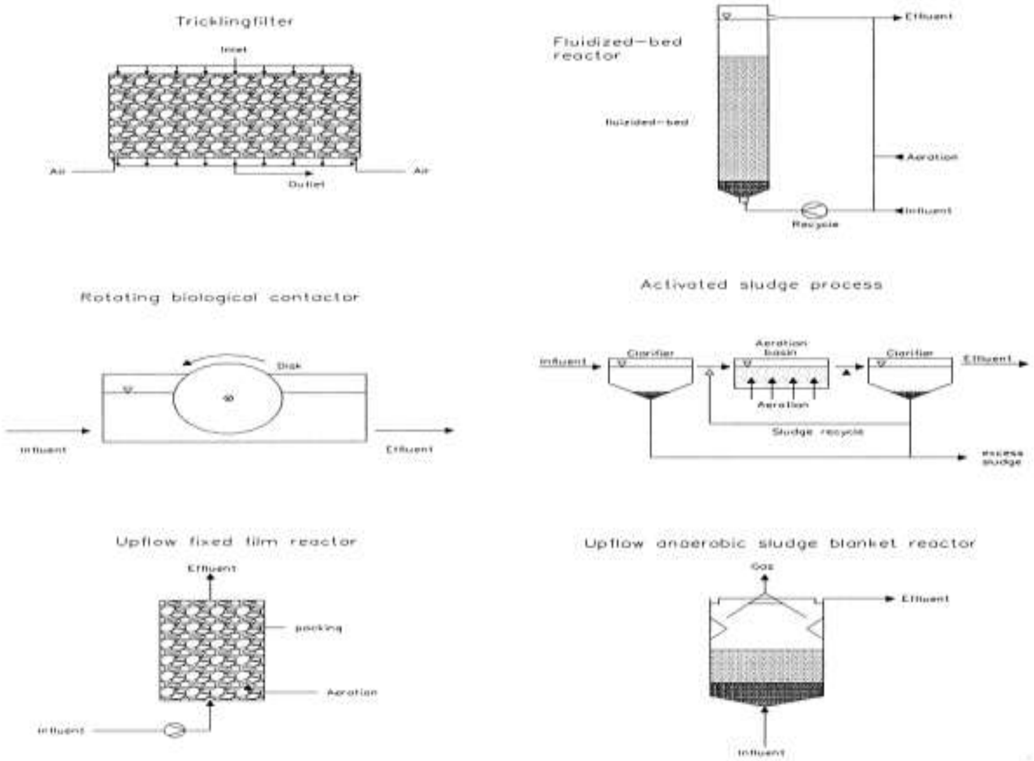

Figure 1: Bioreactors design for water treatment (Langwaldt and Puhakka, 2000)

Traditional techniques for treating water generally cannot get rid of salts. The EIPPCB, which stands for the European Integrated Pollution Prevention and Control Bureau, states that the textile sector releases over 0. 2 million tons of salts into the environment each year. This contributes to changes in aquatic ecosystems. Additionally, the presence of salts in surface waters can negatively influence farming, and the salinization of underground fresh water poses a serious threat to drinking water supplies (Anghem, 1984; Tigini *et al*., 2010).

3.9 Aeration

When oxygen from the air interacts with hydrogen sulfide, it creates sulfate, a form of sulfur that has no smell and dissolves in water. After aeration, some yellow sulfur particles might also appear. In an aeration system, air that is compressed can be added to the water. It is crucial to remove this air afterward to avoid knocking or blockages in the system. Another method involves spraying water into a tank that is not under pressure. A separate pump is required to repressurize the water system. Odors are often noticeable around aeration systems because hydrogen sulfide gas escapes from the water (Mido and Satake 1995; Mathur, 1998; Binnie *et al*., 2002).

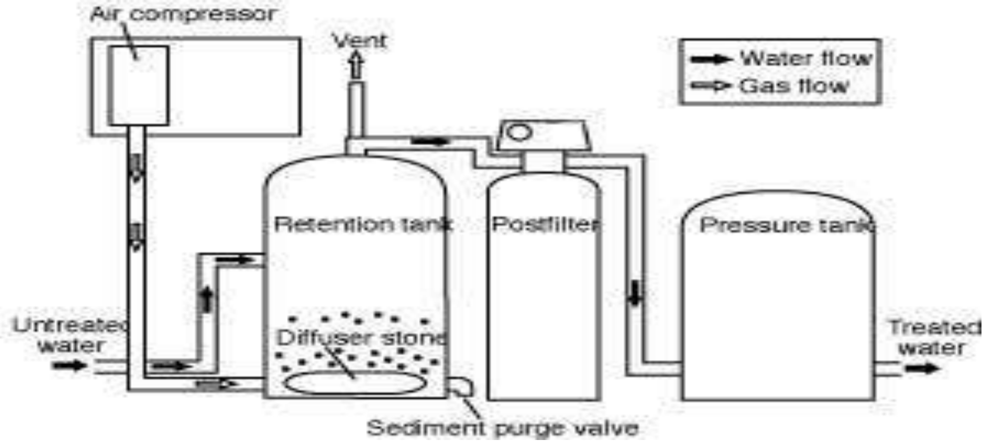

Figure 2: Compressed air aeration system (Binnie *et al*., 2002)

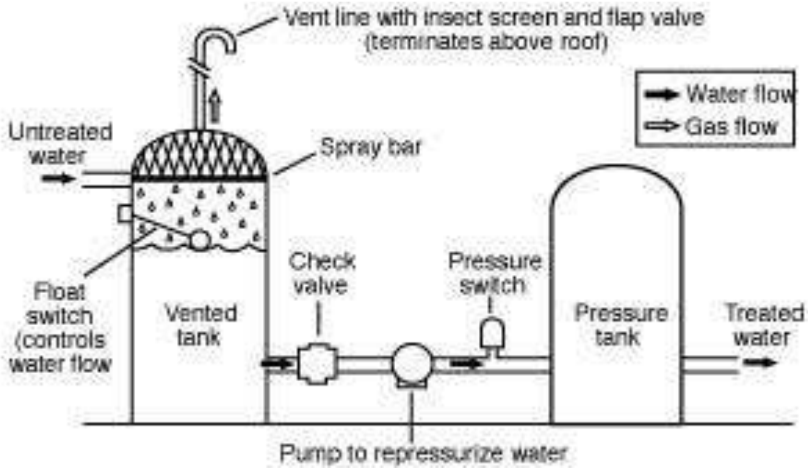

Figure 3: Spray aeration system (Westerville 1996)

3.10 Methane Removal

Methane (CH4) is a hydrocarbon that occurs in nature and is colorless, tasteless, and odorless. It is the main component of natural gas and can create conditions with low oxygen levels, leading to flammable or explosive situations when present in high amounts. Methane is lighter than air and is often eliminated from a well if it is properly vented into the air. Ensuring proper ventilation is crucial as it can greatly lower the levels of methane, which can otherwise result in explosions in confined spaces that contain oxygen, especially when there is a source of ignition like a flame or spark. Additionally, methane can displace air in buildings and replace oxygen within animals' circulatory systems, and its combustion can generate harmful gases, including carbon monoxide (Eltschlager *et al*., 2001; Carson and Mumford, 2002).

3.11 Hydrogen Sulfide Removal

Hydrogen sulfide is produced by sulfur bacteria that can naturally be found in water. These bacteria derive their energy by consuming sulfur present in decaying plants, soil, or rocks, producing hydrogen sulfide as a byproduct. While sulfur bacteria themselves are not harmful, they can lead to unpleasant tastes or smells in water. Typically, water with hydrogen sulfide content does not pose health hazards, but it often carries an annoying "rotten egg" odor and flavor. Water supplies with even 1. 0 ppm (part per million) of hydrogen sulfide can cause corrosion, tarnish copper and silver items, and sometimes release a dark substance that stains linens and porcelain (Busenberg and Plummer, 2000; Manahan, 2004).

3.12 Carbon Filters

Activated carbon filters can remove minimal amounts of hydrogen sulfide from water. The gas adheres to the surfaces of the carbon particles. Depending on the concentration of hydrogen sulfide in the water, these filters must be replaced from time to time. If the levels of hydrogen sulfide are moderate to high, the filter will need to be changed quite often (Bansal and Goyal, 2010; Khan and Ghoshal, 2000).

3.13 Ion Exchange

Ion exchange (IX) represents the most commonly utilized technology for treating nitrates and is implemented at well locations or various entry points into drinking water distribution systems. These systems have treatment capacities that range from below one million gallons each day (MGD) to around 10 MGD. While there have been developments of nitrateselective IX resins, the majority show a greater preference for sulfate over nitrate, hence it is important to consider the effect of sulfate on the nitrate exchange ability (Cheremisinoff, 2001). The design, operation, and monitoring of these technologies are relatively straightforward. They prove to be economically viable for smaller scale applications, such as treating groundwater directly at well heads, and typically include fully automated regeneration sensors and machinery, with regeneration carried out using sodium chloride (Columbus 1995; Sorg, 2003; Chen *et al*., 2006). This approach is optimal for water with total dissolved solids (TDS) levels below 500 mg/l. Over time, resins can become contaminated by salts and organic materials, but many systems manage to function effectively for five to ten years without needing resin changes. A notable downside to these systems is the production and expensive disposal of concentrated brines, which may contain significant amounts of sodium chloride, nitrate, sulfate, and arsenate. Disposal of brines is possible in sewers with sufficient dilution; however, future salinity management might restrict this option in certain regions. Current investigations are focused on biologically processing ion exchange regeneration brines to eliminate nitrate and extend their usability before disposal (Fakhru’lRazi *et al*., 2009). A further significant issue is the removal of nitrate while also addressing the release of nitrosamines or their precursors, which seem to be contaminants or byproducts found in the resins employed (Doudrick *et al*., 2011). Technologies such as pump and treat are applied to remediate contamination sources or plumes to prevent further groundwater pollution by spreading and dissolving contaminants (Cheremisinoff, 2001).

3.14 Metal Removal and Softening

The elimination of heavy metals is a crucial aspect of water treatment processes (Jaishankar *et al*., 2014). In the water treatment system, after the storage tank, a softening process is applied to lessen hardness for purposes such as laundering and bathing. Following the softener, one groundwater system was equipped with an ultraviolet (UV) disinfection lamp to address microbiological issues (A'o, 1998). At each location designated for drinking and cooking water, a reverse osmosis (RO) membrane paired with a booster pump was integrated as an extra safety measure at the kitchen sink. This RO unit decreases levels of sulfate, sodium, total dissolved solids, and hardness—factors that the BAC filter does not address (Center, 2002; Kelada, 2000). Provided that it is managed correctly, the RO system can also eliminate microorganisms, including bacteria, viruses, and parasites (Cobb, 2013).

3.15 Pre-chlorination and Chlorination

The steps taken before chlorination are known as the pre-chlorination stage. Hydrogen sulfide will react rapidly with chlorine, resulting in a colorless, odorless, yellow substance. A small amount of chlorine, often in the form of regular laundry bleach, can be added automatically to any size of water system to eliminate hydrogen sulfide. The yellow sulfur particles that stay in the water can create a yellow film on clothes and fixtures. A sand or aggregate filter is effective in removing these yellow particles. To clear out the built-up sulfur particles, it is necessary to backwash the filter every few days or weeks.

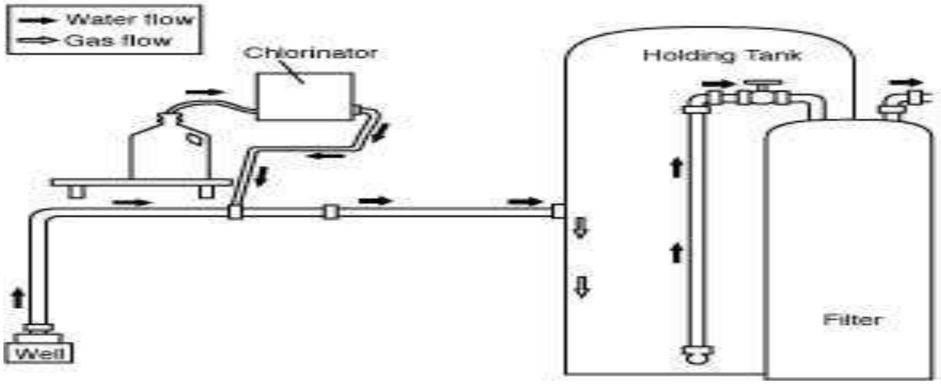

Figure 4: Chlorination system for hydrogen sulfide removal (Cheremisinoff, 2001)

3.16 Disinfection

Newly dug wells or older ones that have been restored often have harmful bacteria and need to be disinfected before they can be used. Chlorine must always be applied outside or in areas with good airflow since inhaling the gases can be harmful. High levels of chlorine can also damage skin and clothing. It is important to mix the chlorine well with the water, and then allow enough time for the chlorine to stay in contact to eliminate all germs and unwanted microorganisms (Cheremisinoff, 2001; Amy *et al*., 2000).

3.17 Fluoridation

This step will remove the fluoride concentration in water.

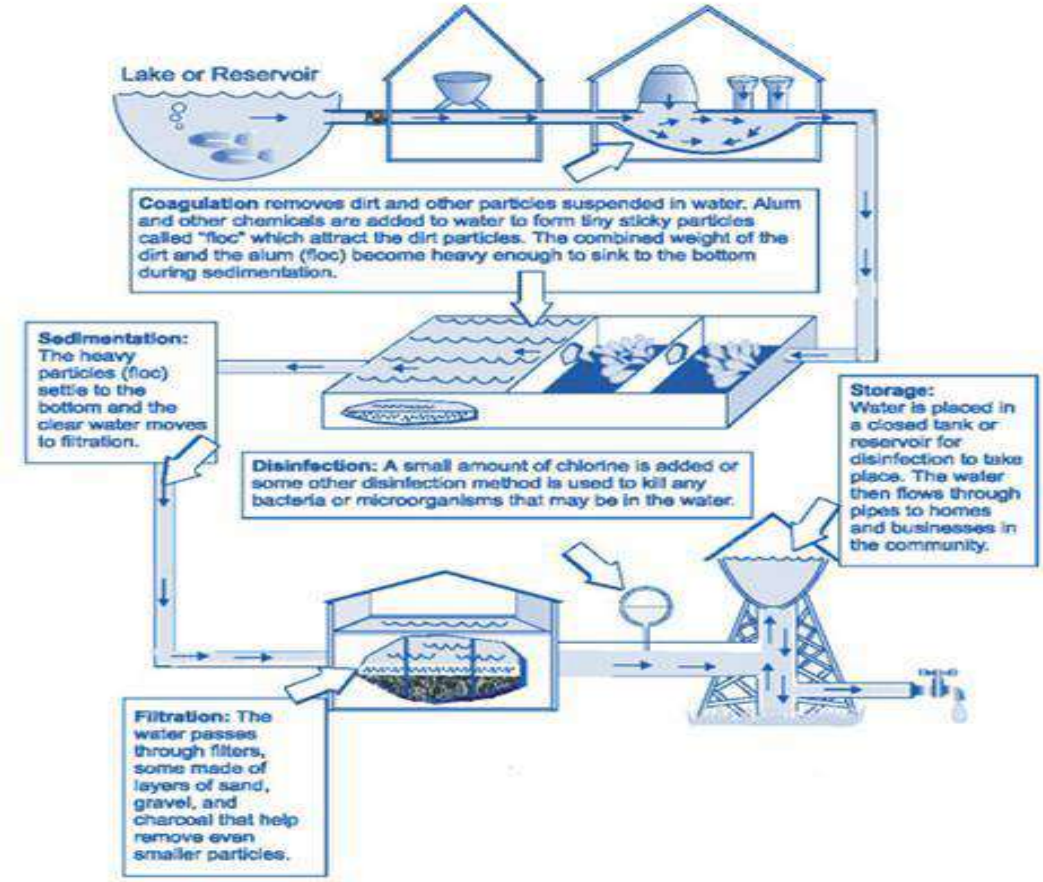

Figure 5: Unit processes of ground water (WHO, 1997)

The presence of nitrate in drinking water presents risks to human health, and the issue of nitrate contamination in groundwater has become widespread in recent times. Research conducted across more than forty states in the United States found that nitrate was the most commonly reported concern regarding groundwater contaminants (Fetter, 1993). Most wells showing high nitrate levels are located in regions that have been used for agricultural purposes. Nitrate, being a stable and highly soluble ion, is challenging to eliminate using traditional methods like coagulation or adsorption. Current methods to treat groundwater contaminated with nitrate include blending and ion exchange, which are the most frequently used techniques, in addition to membrane separation and biological denitrification. The development of chemical denitrification technologies continues (Westerhoff *et al*., 2009; Crittenden *et al*., 2002; Fetter, 1993).

3.18 Blending

Managing groundwater with high nitrate levels primarily involves mixing it with surface water that has lower concentrations of nitrate.

3.19 Biosorption

Biosorption is recognized as one of the best biological methods for removing pollutants from water sources among various approaches. This process involves the removal of materials from a solution using biological material and is categorized as a physicochemical method. Its main benefits are high effectiveness, cost efficiency, and a strong ability to remove pollutants from large volumes of water. There is a significant need to create performance data on either actual or simulated industrial wastewater, as many biological and nonbiological factors can influence the biosorption process (Crini and Badot, 2010).

4. MODERN WATER TREATMENT PROCESSES

4.1 Biological De-nitrification

Microbe-induced nitrate reduction can be accomplished using organic carbon electron donors such as methanol or acetic acid, or inorganic electron donors such as hydrogen or reduced sulfur. However, the dissolved oxygen content of the water must be lowered to about 0.1 mg/l for reduction to occur. Recent advances in hollow-fiber membranes allow autotrophic bacteria to grow on the outside of the membrane in nitrate laden water while hydrogen gas is slowly supplied from within the membranes (Westerhoff *et al*., 2009). Nitrate and oxygen permeate into the biofilms growing on the membranes and are reduced in the anoxic environment within the biofilm; this approach shows significant promise for nitrate reduction. Biological de-nitrification systems do not produce concentrated brine streams, but biofilm growth must be managed (Zhou, 2013). The most significant drawbacks of biological systems are that they require start-up time after prolonged periods of closure (such as in response to seasonal water demand), require more operator support than non-biological systems, and are less mature in the marketplace than IX systems.

4.2 Chemical De-nitrification

Metals such as platinum, palladium, tin and copper can chemically reduce nitrate to other forms, but they usually require a low pH, often need the addition of hydrogen gas or another strong reductant, and perform best with added heat. As a result, full-scale treatment systems based on these catalysts are not yet used for drinking-water applications (Hudlicky,1996). Zero-valent iron (Fe0) has gained the most attention as a nitrate reductant system. Both in-situ groundwater and above-ground treatment systems have been demonstrated at several sites and commercial vendors have recently entered the marketplace. Oxidation of the iron frees electrons, which are then available for nitrate reduction (Westerhoff *et al.*, 2009). Like biological de-nitrification, these systems require low dissolved-oxygen levels to proceed favorably. The precise reactions for zero-valent iron and other chemical reduction processes are not well known for groundwater matrices but in most cases nitrate reduction in groundwater does not proceed to innocuous gases as it does in distilled water or in biological de-nitrification systems (Amy *et al*., 2000). The bioden process is based on the natural biological de-nitrification, which takes place in soil and ground water. However, in this process the de-nitrification is enhanced under controlled conditions in a fixed bed biofilter. In order to meet drinking water requirements, the de-nitrification process needs an aerobic post-treatment. It consists of the following steps such as substrate dosing, denitrifying biofilter, aeration, flock-filtration, polishing filter, safety disinfection, backwash system and backwash water recycling. As substrate a carbon and phosphate source are dosed into the raw water. Normally all other nutrients are normally sufficiently present in the raw water (Wang *et al*., 2005).

4.3 Dissolved Air Floatation (DAF)

The DAF range of water treatment plants excel in treating lake and reservoir water containing high levels of colour, algae and turbidity. The treatment plants also provide excellent treatment of cold water with high levels of iron and manganese (Wang *et al*., 2005). This process offers exceptional algae removal, ease of operation, good tolerance to changing raw water surroundings, rapid start-up, low volumes of plant waste and notably lower building costs (Logsdonl *et al*., 2004).

4.4 Ozonation

It is a water treatment process usually performed to destroy bacteria and other microorganisms through an infusion of ozone. Specifically, it targets cryptosporidium, bacteria and other naturally-occurring organisms. It also reduces the formation of tri-halo-methanes (THMs), which result from the interaction of chlorine and naturally-occurring organic material in the source water (Gottschalk *et al*., 2009).

4.5 Granular activates carbon (GAC) adsorption

GAC features an exceptionally high adsorption surface area, typically ranging from approximately 73 acre/lb (650m^2/gram) to 112 acre/lb (1000 m^2/gram). It consists of small groups of carbon atoms that are layered together. This material is created by heating a carbon source—such as coal, lignite, wood, nutshells, or peat—in a way that excludes air, resulting in a substance with a high carbon content (Cheremisinoff and Rosenfeld, 2009; Perry *et al*., 1997).

4. 6 Membrane based processes

Reverse osmosis (RO) and electrodialysis (ED) are costly methods for eliminating nitrate, and they are mainly employed to treat water that contains high total dissolved solids (TDS) rather than just nitrate pollution. Currently, these techniques are used in smaller communities and military installations for nitrate removal (Kumar and Shah, 2006). Systems based on ED use electrical current to move either positive ions (cations) or negative ions (anions) through a semipermeable membrane. The current can be tuned to allow only cations to pass through while keeping out anions like nitrate. Nevertheless, these membrane technologies need large amounts of external energy, leading to high operational expenses (Ganzi *et al*., 2010). Both RO and ED generate concentrated brine streams that must be disposed of; typically, pretreatment is needed to avoid membrane fouling. Processes involving membranes like these can be a feasible treatment choice for towns that have existing membrane technologies (Greenlee *et al*., 2009; Mujeriego, and Asano, 1999).

5. PHYSICAL AND CHEMICAL CHARACTERIZATION OF WASTEWATER

The following physical and chemical descriptions apply to many types of wastewater, including both municipal and industrial sources.

5.1 Physical Attributes

Key physical attributes of wastewater are the content of solids, its color, smell, and temperature.

5.1.1 Total Solids

The total solids present in wastewater comprise both insoluble or suspended solids and soluble materials mixed in the water. To determine the amount of suspended solids, the sample is filtered, and the remaining residue is dried and weighed. When this residue is heated, the volatile solids are incinerated. These volatile solids are typically considered organic matter, although not all organic substances combust, and some inorganic salts decompose when subjected to high heat. The organic substances primarily consist of fats, carbohydrates, and proteins. In an average wastewater sample, about 40 to 65 % of the solids are usually suspended. Settleable solids are quantified in milliliters per liter, referring to those that can be eliminated through sedimentation. Approximately 60 % of the suspended solids in typical municipal wastewater can be settled (Ron & George, 1998). Solids can also be categorized based on their behavior at high temperatures (600 °C): those that vaporize are termed volatile solids, while those that do not are fixed solids. Generally, volatile solids are of an organic nature.

5.1.2 Color

Color serves as a qualitative measure that can indicate the overall state of wastewater. Wastewater appearing light brown is generally less than 6 hours old, while a light to medium gray hue suggests some level of decomposition or that it has spent time within the collection system. Conversely, dark gray or black wastewater typically indicates septic conditions, largely resulting from significant bacterial breakdown in anaerobic environments. The darkening often occurs due to the creation of various sulfides, especially ferrous sulfide, which forms when hydrogen sulfide generated in anaerobic settings interacts with divalent metals like iron that may be present. Colors are assessed through comparisons with established standards.

5.1.3 Odor

Recognizing odors has gained importance as public awareness regarding effective wastewater treatment operations has grown. Fresh wastewater generally has a mild smell, but various odorous substances emerge when it undergoes biological decomposition in anaerobic environments. The different unpleasant odours produced by certain industrial wastewater are presented in Table 1.

Table 1: Unpleasant Odours in Some Industries (Brault, 1991)

Industries	Origin of odours
Cement works, lime kilns	Acrolein, amines, mercaptans, dibutyl sulphide, H_2S, SO_2, etc.
Pharmaceutical industries	Fermentation produces
Food industries	Fermentation produces
Food industries (fish)	Amines, sulphides, mercaptans
Rubber industries	Sulphides, mercaptans
Textile industries	Phenolic compounds
Paper pulp industries	H_2S, SO_2
Organics compost	Ammonia, sulphur compounds

5.1.4 Temperature

The temperature of wastewater tends to be greater than that of the water supply, mainly due to the addition of warm municipal water. Monitoring the temperature is crucial as many wastewater treatment systems rely on biological processes that depend on temperature. The temperature of wastewater fluctuates with the seasons and also differs by geographic area. In colder regions, temperatures range roughly from 7 to 18 °C, whereas in warmer areas, they fall between 13 and 24°C (Ron & George, 1998).

5.2 Chemical characteristics

5.2.1 Inorganic chemicals

The main chemical analyses encompass free ammonia, organic nitrogen, nitrites, nitrates, as well as organic and inorganic phosphorus. Nitrogen and phosphorus hold significance because they are the nutrients that promote the growth of aquatic vegetation. Additional tests, including chloride, sulfate, pH, and alkalinity, are carried out to evaluate the feasibility of recycling treated wastewater and managing different treatment processes (Rein, 2005).

Trace elements, such as certain heavy metals, are not routinely tested, but they may influence the biological treatment aspect of wastewater. Various living organisms require different quantities of essential trace elements like iron, copper, zinc, and cobalt for healthy growth. Heavy metals can be harmful as well, making it especially necessary to assess their levels, particularly when considering the subsequent use of treated effluent or sludge. Many of these metals are also recognized as priority pollutants, including arsenic, cadmium, chromium, and mercury.

Gas measurements, including hydrogen sulfide, oxygen, methane, and carbon dioxide, are taken to assist system functionality. It is important to check for hydrogen sulfide not only because it is a smelly and highly toxic gas but also due to its potential to cause corrosion, affecting the maintenance of long, flat sewers. Dissolved oxygen levels are monitored to oversee aerobic biological treatment methods. Methane and carbon dioxide readings are relevant to the management of anaerobic digesters.

5.2.2 Organic chemicals

Various tests to assess the organic matter in wastewaters have been created over time. Generally, tests can be categorized into those that identify significant concentrations of organic material exceeding about 1 mg/l and those that detect trace amounts in the range of 1012 to 103 mg/l. Common laboratory methods for measuring significant levels of organic matter in wastewater (over 1 mg/l) include (1) biochemical oxygen demand (BOD), (2) chemical oxygen demand (COD), and (3) total organic carbon (TOC). For trace organics ranging from 1012 to 103 mg/l, instrumental techniques, like gas mass spectroscopy and chromatography, are employed. Specific organic compounds are examined to identify priority pollutants (Metcalf & Eddy, 1991). The BOD, COD, and TOC tests provide a general measure of organic content but do not indicate how the wastewater reacts to various biological treatment methods.

5.2.3 Volatile organic carbons (VOC)

Volatile organic compounds, including benzene, toluene, xylenes, trichloroethane, dichloromethane, and trichloroethylene, are frequently found as pollutants in the soil of industrial and commercial regions. A major reason for these pollutants is the leakage from underground storage tanks. Furthermore, solvents that have been improperly discarded and landfills created before stricter regulations are also key contributors to soil VOCs. Many of these organic compounds are identified as priority pollutants, such as polychlorinated biphenyls (PCBs), polycyclic aromatics, acetaldehyde, formaldehyde, 1,3butadiene, 1,2dichloroethane, and hexachlorobenzene (HCB). A list of typical organic and inorganic substances that can be found in industrial waste is provided.

Table 2: Substances present in industrial effluents (Bond & Straub, 1974)

Substances	**Present in Wastewaters from**
Acetic acid Acetate rayon	beet root manufacture
Acids	Chem. manufacture, mines, textiles manufacture
Ammonia	Cotton and straw kiering, wool scouring
Arsenic	Sheep dipping
Cadmium	Plating
Chromium	Plating, chrome tanning, alum anodizing
Citric acid	Soft drinks and citrus fruit processing
Copper	Copper plating, copper pickling
Cyanides	Gas manufacture, plating, metal cleaning
Fats, oils, grease	Wool scouring, laundries, textile industry
Fluorides	Scrubbing of flue gases, glass etching
Formaldehyde	Synthetic resins and penicillin manufacture
Free chlorine	Laundries, paper mills, textile bleaching
Hydrocarbons	Petrochemical and rubber factories
Mercaptans mills	Oil refining, pulp
Nickel Plating	Nickel Plating
Nitro compounds	Explosives and chemical works
Organic acids	Distilleries and fermentation plants
Phenols	Gas and coke manufacture chem. plants
Starch	Food processing textile industries
Sugars	Dairies, breweries, sweet industry
Sulfides	Textile industry, tanneries, gas manufacture
Sulfites	Pulp processing viscose film manufacture
Tannic acid	Tanning , sawmills
Tartaric acid	Dyeing, wine, leather, chem. manufacture
Zinc	Galvanizing zinc plating, rubber process.

5.2.4 Heavy metals and inorganic species

Various sectors release heavy metals into the environment, with chromium being the most commonly utilized and emitted metal from a range of sources. Among the many pollutants that enter water ecosystems, such as mercury, lead, pesticides, and herbicides, many are extremely harmful to living beings. They can reduce the chances of reproduction, block appropriate growth and development, and can even lead to death.

Nevertheless, chromium is not the most harmful metal to life. Substantially more toxic are elements like cadmium, lead, and mercury. These metals have a strong attraction to sulfur and disrupt enzyme activity by creating connections with the sulfur groups within enzymes. Additionally, heavy metals also chemically bond with carboxylic acid (CO2H) and amino (NH2) groups in proteins. Ions of cadmium, copper, lead, and mercury attach to cell membranes, which obstructs the transport processes across the cell wall. Heavy metals can also cause phosphate biocompounds to form precipitates or trigger their breakdown. Heavy metals found in major industries shown in Table 3.

Table 3: Heavy Metals Found In Major Industries (Bond &Straub, 1974)

Industry	**A**	**As**	**Cd**	**Cr**	**C**	**Hg**	**Pb**	**Ni**	**Zn**
Pulp & paper mills				X	X	X	X	X	X
Organic chem.	X	X	X	X		X	X		X
Alkalis, Chlorine		X	X	X		X	X		X
Fertilizers	X	X	X	X	X	X	X	X	X
Petroleum refining	X	X	X	X	X		X	X	X
Steel works		X	X	X	X	X	X	X	X
Aircraft plating, finishing			X	X	X	X		X	
Flat glass, cement				X					
Textile mills				X					
Tanning				X					
Power plants				X					

The presence of cadmium in water can result from discharges from industries and waste from mining activities. This metal is commonly employed in metal plating. Cadmium shares many chemical characteristics with zinc, which means they often interact in geological processes. In water, both of these metals exist in the +2 oxidation state. Acute exposure to cadmium can lead to severe health issues in individuals, including elevated blood pressure, damage to kidneys, destruction of testicular tissues, and the breakdown of red blood cells. In some enzymes, cadmium can take the place of zinc, which alters the enzyme's structure and reduces its ability to function effectively. Water and sediment in industrial harbor areas often see pollution from cadmium and zinc. In water, inorganic lead from various industrial and mining activities is also present in the +2 oxidation state. Lead from leaded gasoline was historically a major contributor to lead in the air and on land, much of which ultimately filters into natural water sources. Acute lead poisoning in humans results in grave damage to organs including the kidneys, reproductive system, liver, as well as the brain and nervous system. Mercury typically appears as a minor component in several minerals, with an average presence of about 80 ppb or slightly lower in continental rocks. Cinnabar, or red mercuric sulfide, is the primary ore for commercial mercury. Metallic mercury finds its use as an electrode in generating chlorine gas electrolytically, in laboratory vacuum equipment, and in various other applications. In the past, organic mercury compounds were widely utilized as pesticides, especially in fungicides. The element mercury can enter the environment from numerous human related activities. Such sources include discarded laboratory products, batteries, broken thermometers, lawn fungicides, dental amalgam, and pharmaceutical items. Sometimes, sewage discharge can carry mercury levels that are significantly higher than those found in typical natural waterways. The dangers of mercury were tragically highlighted in Japan's Minamata Bay between 1953 and 1960, where 111 cases of mercury poisoning and 43 fatalities occurred among individuals consuming contaminated seafood from the bay. Neurological effects from mercury exposure included irritability, paralysis, blindness, insanity, chromosome damage, and birth defects (Rein, 2005).

5.2.4.1 Cyanide

Among the various inorganic substances present in wastewater, the cyanide ion, CN, stands out as particularly significant. As a highly toxic compound, cyanide appears in water as HCN, which is categorized as a weak acid. The cyanide ion has a strong tendency to bond with several metal ions, creating less harmful compounds like ferrocyanide, $Fe(CN)_{64}$, when it reacts with iron (II). The volatile form of HCN is extremely harmful and has been infamously used in execution methods in gas chambers in the United States. In industry, cyanide is frequently used for cleaning metals and in the process of electroplating. It is also a major pollutant in effluents from gas works and coke ovens. Certain mineral processing operations make extensive use of cyanide.

5.2.4.2 Ammonia

Ammonia forms as the first product when nitrogen containing organic materials break down, and its detection often signals the existence of such materials. Some groundwater sources normally contain ammonia, and it is occasionally added to drinking water to mask the taste and smell of free chlorine. Due to the pKa, which is the negative logarithm of the acid ionization constant, of ammonium ion (NH_4 +) being 9. 26, most of the ammonia found in water exists in the form of NH_4+ rather than NH_3.

6. CONCLUSION

Ultimately, in regions facing environmental challenges and limited water supply, recycling wastewater stands out as an essential strategy for achieving effective water management. Utilizing advanced wastewater treatment technologies and reusing the treated water significantly lessens the reliance on conventional water sources, especially as the demand for fresh water continues to rise. By extracting components like energy and nutrients from wastewater, it is possible to create a circular economy model that enhances resource efficiency and supports environmental sustainability, while minimizing ecological harm. Nevertheless, there are numerous challenges despite the evident benefits of wastewater recycling. Key issues include improving public attitudes, ensuring the safety and quality of the recycled water, and securing funding for required technology and infrastructure. The pursuit of effective water management will find a promising path through the recycling of wastewater. As awareness increases and technological advances continue, incorporating recycled water into everyday life is poised to be a significant solution addressing global water issues, contributing to a more sustainable and resilient future for everyone.

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