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Groundwater Treatment Technologies for Ensuring Safe and Sustainable Water

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Abstract

Water is an essential resource that supports life, ecosystems, and human advancement. Among its various sources, groundwater holds a vital component of the hydrological cycle. Groundwater is an important resource that supports agricultural, industrial and domestic activities. However, its overexploitation and contamination have leads to declining water levels and quality of water leads to serious environmental challenges. Effective groundwater treatment ensures its sustainability and secure use. Treatment methods can be compartmentalizing into physical, chemical, and biological processes. Physical treatments including sedimentation, aeration, and filtration are used to remove suspended solids and dissolved gases. Chemical treatments including chlorination, coagulation, and ion exchange, are use to eliminating pathogens, heavy metals, and chemical pollutants. Biological processes including bioremediation and constructed wetlands, utilize microbial activity to destroy the organic pollutants and enhance water quality. Advanced treatment methods including reverse osmosis, advanced oxidation processes (AOPs), ultraviolet (UV) disinfection, ozonation, activated carbon filtration, membrane bioreactors (MBR), electrocoagulation, and photocatalytic water purification and Nano filtration gives higher efficiency in removing complex pollutants and recharging groundwater quality. The parameters like nitrates, fluorides, chlorides, total dissolved solids (TDS), and the presence of pathogens are vital for water quality evaluation. Increased nitrate levels indicate contamination from fertilizers and sewage. Small amount of Fluoride beneficial for dental health, but excessive, lead to fluorosis. The source of Chlorides from industrial activities causing taste and corrosion potential. Total Dissolved Solids affecting the water hardness. Pathogens leads to microbial contamination and affect the purity of water. It is essential to ensure the quality and safety of water for consumption and other uses.

Keywords: *Water resource; Water quality parameters; Groundwater Treatment; Aquifer sustainability; Water consumption*

1. Introduction

Water is a scentless fluid which comprised of two components: hydrogen and oxygen. Water is fundamental for all living things since it assists in numerous significant cycles with hydration, processing, and temperature guideline. It exists in three states: fluid, ice and gas. Water comes from various natural sources like rainwater, river and streams, lakes and ponds, groundwater, ice capes, oceans, desalination ponds. Each of these sources plays an important role in providing water for drinking, agriculture, and industry. Groundwater is water that's crammed in the tiny gaps between rocks soils and sediments under the ground. A full body of groundwater is called an aquifer. Straight down through the soils to an aquifer the level underground where the groundwater hit first is called the water table. Below the water table the ground is completely soaked or saturated with water is called the saturated zone. The area above the water table is called the unsaturated zone. Groundwater plays a crucial role as a source of water because it provides a reliable and often clean supply, especially in areas where surface water is limited. Groundwater likewise assumes a vital part in supporting metropolitan and rustic water supplies, guaranteeing networks approach spotless and dependable drinking water. Moreover, it serves ventures requiring water for processes like cooling, cleaning, or creation. In locales with occasional dry seasons or unpredictable precipitation, groundwater turns out to be considerably more significant, going about as a hold that supports environments and jobs during dry periods. The meaning of groundwater couldn't possibly be more significant. It is a significant supporter of the worldwide water supply, supporting roughly 40% of the world's drinking water needs and around half of farming water system. Groundwater is a steadier and dependable source than surface water, as it is less powerless to the fluctuation brought about via occasional weather conditions or surface water pollution. Moreover, it keeps up with natural equilibrium by taking care of wetlands, streams, and springs, which are fundamental for biodiversity and territory protection. Groundwater treatment is expected to guarantee that the water is alright for human utilization, horticultural use, and modern applications. While groundwater is in many cases considered a cleaner wellspring of water because of its normal filtration through soil and rock, it can in any case be sullied by different elements. These incorporate horticultural spillover, modern waste, sewage, and regular components like arsenic or fluoride, which can present huge wellbeing gambles when consumed at raised levels. Groundwater may likewise contain microbes, weighty metals, or abundance minerals that influence water quality and cause medical issues, like gastrointestinal illnesses, harming, or long haul ongoing circumstances. Moreover, contaminations like nitrates from composts can corrupt water quality, while elevated degrees of broken up solids can influence the taste and hardness of water, making it unsatisfactory for utilization or use in specific ventures. Hence, treatment strategies are vital to eliminate these impurities, guaranteeing the water satisfies wellbeing and security guidelines for drinking, water system, and other fundamental exercises. Treatment likewise works on the water's stylish characteristics, like lucidity and taste, upgrading its general reasonableness for day to day use. Notwithstanding developing water shortage and contamination, legitimate treatment guarantees the maintainability of groundwater as a fundamental asset. Many high level treatment techniques, for example, switch assimilation and high level oxidation processes, require huge energy input, driving up costs. The foundation and hardware expected for treatment — like filtration frameworks, siphons, and films — can be exorbitant to introduce, work, and maintain. Groundwater can contain different impurities, including natural contaminations, weighty metals, and microorganisms, making treatment more perplexing and requiring specific advancements for their removal. In many cases, groundwater is obtained from profound underground or in far off areas, requiring costly extraction, transportation, and treatment offices to make it available for use. Constant checking to guarantee water quality norms are met, and customary support of treatment frameworks, likewise add to the continuous costs. These factors by and large add to the cost of groundwater treatment, however they are fundamental to guaranteeing that the water stays protected and economical for human use and ecological wellbeing. Groundwater treatment is necessary for safe and long term use.

2. Groundwater Pollution

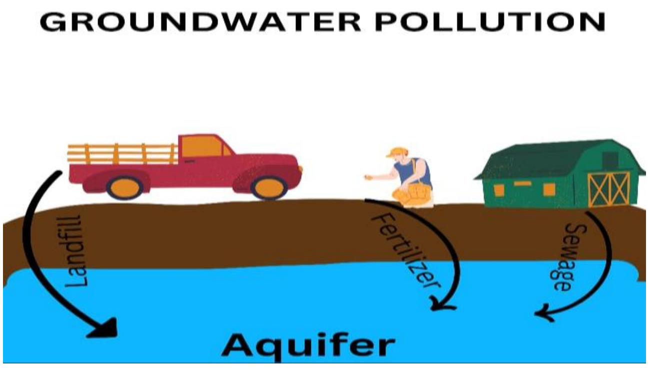

Figure 1 Groundwater Pollution

When unsafe water or substance enters the ground the ground water gets contaminated which may from human activities like improper garbage disposal, releasing sewers, unnecessary compost use and so forth. Some natural impurities like arsenic, fluoride, chloride can also cause groundwater pollution. Contaminated groundwater may result in spread of waterborne sicknesses, unsafe for people and untamed life. So it is necessary to treat the ground water for sustainable use (Figure 1).

3. Physical Treatment

It is the essential process for removing the contaminants from groundwater. Sedimentation is the process of removing suspended impurities by allowing the water to stay undistrubed for some time in large tanks where most of the suspended particles settle down due to the force of gravity. Aeration is the process of bringing the water in contact with air, the water absorbs oxygen from the air. An aeration system is used to oxidize Dissolve iron, manganese or hydrogen sulphide in water, converting these contaminants into a form they can be easily filtered out. Filtration is the process of purifying water by passing through a bed of sand or fine granular material.

4. Chemical Treatment

4.1.Chlorination

Chlorination is the method involved with adding chlorine or chlorine mixtures to water to clean and eliminate unsafe microorganisms like microbes, infections, and protozoa. It is one of the most regularly involved strategies for sanitizing drinking water, wastewater, and groundwater because of its viability and relatively minimal expense. Chlorine is added at the underlying phase of water treatment. Helps control natural development, green growth, and other natural matters. The expected measure of chlorine is added to kill microorganisms. Guarantees the water is liberated from microscopic organisms, infections, and protozoa. Chlorine needs time to follow up on microorganisms. The adequacy relies upon chlorine focus and water temperature. A limited quantity of chlorine stays in the water after treatment. Forestalls repeated pollution in the appropriation framework. Overabundance chlorine is taken out utilizing synthetic substances like sulfur dioxide or enacted carbon. Diminishes the gamble of chlorine-related taste, smell, and medical problems. In the sorts of Chlorination Processes, Continuous Chlorination is a chlorine is added constantly to keep a lingering level in water. It is utilized in metropolitan water supplies to guarantee progressing sterilization. Shock Chlorination is high portion of chlorine is applied for a brief time frame.It is utilized for sanitizing wells, capacity tanks, and crisis water treatment. In Breakpoint Chlorination process, chlorine is added until it totally reacts with alkali and natural matter. Guarantees viable sterilization by dispensing with joined chlorine compounds. Superchlorination is high chlorine portion is utilized to major areas of strength for kill. Overabundance chlorine is subsequently taken out through dechlorination before utilization. Dechlorination is the most common way of eliminating overabundance chlorine from treated water. Synthetic compounds like sulfur dioxide, sodium bisulfite, or enacted carbon are utilized. The benefits of Chlorination is to kills most microscopic organisms, infections, and microorganisms. Keeps a chlorine level in the circulation framework, forestalling repeated pollution. Less expensive than other sanitization strategies like ozonation or UV treatment. Easy to utilize and screen in civil and modern settings. Forestalls bacterial regrowth in pipelines and capacity tanks. The disadvantages of Chlorination are chlorine responds with natural matter, framing hurtful mixtures like trihalomethanes (THMs) and haloacetic acids (HAAs), which are connected to wellbeing gambles. Chlorine doesn't really kill specific protozoa like Cryptosporidium and Giardia. Can grant areas of strength for an and smell to drinking water. Can harm lines and framework over the long run. Chlorine gas and fluid chlorine are dangerous and require appropriate capacity and taking care of. chlorination reduces the effect of pathogenic infection. It may effect to a chemical threat to human health because of disinfection residues and byproducts [1]. Chlorination stays one of the most broadly utilized water treatment strategies because of its productivity, moderateness, and capacity to give leftover insurance. Nonetheless, it is vital for screen chlorine levels cautiously to limit wellbeing gambles related with sterilization side-effects. Elective sterilization techniques, like UV treatment or ozonation, might be utilized in blend with chlorination for further developed water quality.

4.2.Ozonation

Ozonation is a water treatment process that uses ozone (O_3), a strong oxidant, to clean and eliminate pollutants. Ozone, a gas composed of three oxygen atoms, is more effective than chlorine in killing microbes, viruses, and other microorganisms. The process of ozonation begins with the generation of ozone, typically through Crown Discharge, where electrical discharges split oxygen molecules (O_2) into individual atoms that recombine to form ozone (O_3), or through Bright Radiation (UV), where UV light splits oxygen molecules to create ozone. The ozone is then infused into the groundwater using diffusers or mixing systems. It reacts with both organic and inorganic contaminants, breaking them down or making them easier to remove. After oxidizing the pollutants, ozone naturally decomposes back into oxygen (O_2), leaving no harmful residues behind. catalytic mechanism and influencing factors of the catalytic ozonation system for removing organic pollutants in water [2-3]. There are two main types of ozonation systems: In-Situ Ozonation, where ozone is injected directly into groundwater through wells for onsite treatment, and Ex-Situ Ozonation, where groundwater is pumped to a treatment plant, and ozonation occurs in a controlled system. The benefits of ozonation include its ability to kill bacteria, viruses, and protozoa more efficiently than chlorine, remove iron, manganese, hydrogen sulfide, and organic contaminants, and eliminate unpleasant odors and tastes in water. Unlike chlorine, ozone doesn’t leave harmful byproducts, and it works quickly compared to other chemical treatments. However, ozonation has its disadvantages, such as the need for expensive ozone generators and high energy consumption, as ozone rapidly decomposes and requires continuous generation. Additionally, ozone systems require skilled operation and maintenance, and if bromide is present in the water, ozonation can produce harmful byproducts like bromate. It is used in municipal water treatment plants and industries. It requires the water as high quality. In the catalytic ozonation system, catalytic mechanism to removing the organic pollutants in water [33].

4.3.Coagulation and Flocculation

Coagulation and flocculation are key processes in water treatment used to remove suspended particles, organic matter, and other contaminants, helping to clarify water and enhance filtration efficiency. Coagulation involves the addition of chemical compounds, known as coagulants, to weaken suspended particles, allowing them to clump together. Flocculation follows as a gentle mixing process that encourages the weakened particles, now called flocs, to grow in size so they can be removed through sedimentation or filtration. Common coagulants include alum ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), and polyaluminum chloride (PAC), which neutralize the negative charge on particles, enabling them to come together. Rapid mixing helps evenly distribute the coagulant, initiating particle aggregation, while slow mixing allows the smaller particles to collide and form larger, heavier flocs. Polymers, or flocculants, may also be added to strengthen and increase the size of the flocs, which then settle to the bottom in a sedimentation tank or are removed by filtration. Coagulation process is used to remove natural organic matters (NOM) and for water color[5-7].There are different types of coagulation and flocculation processes, including chemical coagulation, which uses coagulants like alum, ferric chloride, or PAC to neutralize particle charges; electrocoagulation, which uses electricity to dissolve metal particles like iron or aluminum that act as coagulants; and organic flocculation, which utilizes biopolymers or natural substances such as starch or chitosan to aggregate particles. The advantages of coagulation and flocculation include their effectiveness in removing turbidity, color, and pathogens, enhancing filtration and sedimentation efficiency, and eliminating heavy metals and organic matter [8]. Additionally, chemical coagulation is relatively low-cost. However, there are disadvantages, such as the production of sludge that requires disposal, high chemical costs for large-scale treatment, the need for careful pH control to ensure optimal performance, and the potential for residuals to remain in the water, especially when using coagulants like alum. Coagulation and flocculation are widely used in both drinking water and wastewater treatment to improve water quality and efficiency in subsequent treatment steps [9-11].

4.4.Water Softening

Water softening is the process of removing hardness-causing minerals, primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}), from water. Hard water leads to scaling in pipes, reduces the effectiveness of soap, and can interfere with industrial processes. The water softening process begins when hard water passes through a resin bed containing sodium (Na^{+}) or potassium (K^{+}) ions. These ions exchange places with the calcium and magnesium ions in the water, making it softer [12]. The resin is periodically regenerated using a salt solution (NaCl or KCl) to restore its ion-exchange capacity. Additionally, chemicals like lime ($Ca(OH)_2$) and soda ash (Na_2CO_3) are added to the water, which react with calcium and magnesium to form insoluble compounds. These compounds are then removed through sedimentation and filtration. [13] The removal of calcium, magnesium, and ions from water is water softening process. The presence of these constituents in untreated water develops difficult in dissolving the positive charged ions. The undesirable minerals are taken out from the water by water softening process treatment [21]. There are several types of water softeners, including Ion Exchange Softeners, which are commonly used for both household and industrial applications; Lime-Soda Softening, which is used in large-scale water treatment plants; Electromagnetic or Magnetic Water Softeners, which are less effective and primarily used for prevention rather than removal. The benefits of water softening include the prevention of scale buildup in pipes, boilers, and appliances, improved soap and detergent efficiency, extended lifespan of plumbing and equipment, and reduced energy consumption in heating systems. However, there are some drawbacks, such as increased sodium levels in the water, which can be a concern for people on low-sodium diets. Water softeners also require regular maintenance, including the regeneration of the resin in ion exchange systems, and wastewater discharge from the softening process can raise environmental concerns. Additionally, water softening is not effective in removing other pollutants, such as bacteria, heavy metals, or nitrates.

4.5.Water PH Adjustment

Water pH adjustment involves altering the pH level of water to maintain its stability, prevent corrosion, and enhance overall water quality. The process begins by measuring the current pH level using pH meters or test kits, followed by determining the desired pH based on the intended water use, such as drinking water or industrial applications. Changing the Ph of wastewater assists with bettering concentrate unsafe synthetics like quinolones and sulfonamides. By making the watermore acidic or fundamental, these synthetics can be taken out more without any problem. This makes the extraction cycle more precise and effective It additionally helps the expectional dissolvable stay powerful, further developing the general water treatment [48]. Acids or bases are then added to raise or lower the pH as needed, with careful mixing to ensure the chemical is evenly distributed. Afterward, the pH is measured again to confirm the desired adjustment. There are two main types of pH adjustment: pH increase, which is used to raise the pH of acidic water to neutral or alkaline levels, typically employing chemicals like lime ($Ca(OH)_2$), sodium hydroxide (NaOH), or soda ash (Na_2CO_3). This process is commonly used to prevent pipe corrosion and improve the taste of the water. The second type, pH reduction, is used to lower the pH of alkaline water to neutral or acidic levels, using chemicals such as sulfuric acid (H_2SO_4), hydrochloric acid (HCl), or carbon dioxide (CO_2). This is applied to prevent scale formation in pipes and equipment. The benefits of pH adjustment include the prevention of pipe corrosion and scaling, improved taste and odor of water, enhanced effectiveness of other water treatment processes, and protection of water distribution systems and appliances. However, pH adjustment has its drawbacks, such as the potential for causing health issues or system damage if the adjustment is too extreme, the need for careful monitoring and chemical handling, and the possibility of unwanted byproducts from certain chemicals. Overall, pH adjustment is a crucial step in water treatment to ensure the safe and efficient use of water.

4.6.The Advanced Oxidation Process (AOP)

The Advanced Oxidation Process (AOP) refers to treatment methods that generate highly reactive hydroxyl radicals (OH) to degrade both organic and inorganic contaminants in water. These radicals are powerful oxidants that break down pollutants into harmless substances such as water, carbon dioxide, and mineral salts. AOPs employ chemical, photochemical, or electrochemical techniques to produce these radicals, which then react with contaminants to break chemical bonds, converting them into simpler, non-toxic molecules. Ideally, the process transforms pollutants into carbon dioxide, water, and inorganic particles. There are several types of AOPs, including hydrogen peroxide-based AOPs, where hydrogen peroxide (H_2O_2) reacts with UV light or ozone (O_3) to generate hydroxyl radicals. Ozone-based AOPs involve ozone (O_3) interacting with UV light or hydrogen peroxide (H_2O_2) to produce additional hydroxyl radicals. Fenton's reaction (Fe^{2+}/H_2O_2) utilizes ferrous iron (Fe^{2+}) and hydrogen peroxide to generate hydroxyl radicals, with the process being enhanced by UV light in the Photo-Fenton process for increased efficiency. Electrochemical AOPs use electricity to generate radicals from water molecules and other oxidants, while ultrasound AOPs employ high-frequency sound waves to create cavitation bubbles that produce hydroxyl radicals. The benefits of AOPs include their high efficiency in removing persistent organic pollutants and microorganisms, their ability to degrade a wide range of contaminants, and the lack of harmful residual toxicity, unlike chlorination. AOPs also improve biodegradability by converting complex toxins into simpler, more biodegradable forms. However, there are some drawbacks, including high energy costs for UV-based and electrochemical methods, the need for pre-treatment as suspended solids and certain ions (e.g., bicarbonates) can reduce efficiency, and the risks associated with handling chemicals like hydrogen peroxide and ozone. It weakens a variety of growing pollutants by yielding highly sensitive free radicals [30-33]. Generation and regulation of high-valent metal species in advanced oxidation processes. Additionally, some byproducts of AOPs may require further treatment for complete mineralization. AOPs are commonly used to remove drugs, pesticides, and industrial pollutants from groundwater [34].

4.7.Precipitation

Precipitation is a chemical process used to remove dissolved contaminants from water by converting them into solid particles that can be separated. This is achieved by adding specific chemicals that react with the impurities to form insoluble compounds. The process begins by adding a precipitating agent, such as lime, alum, or ferric chloride, to the water. These chemicals react with dissolved contaminants, forming solid particles, or "precipitates." Coagulants are used to help small particles aggregate into larger flocs, which then settle to the bottom of a tank. The remaining fine particles are removed through sand or membrane filtration, and the settled solids, or sludge, are removed and treated appropriately.There are several types of precipitation processes, including lime softening, which removes hardness (calcium and magnesium) by adding lime ($Ca(OH)_2$); metal precipitation, which eliminates heavy metals like lead, chromium, and arsenic using hydroxide or sulfide precipitation; phosphate precipitation, commonly used in wastewater treatment to remove phosphates with aluminum or iron salts; sulfide precipitation, used to remove toxic metals with sulfide compounds; and carbonate precipitation, which helps remove calcium by adding sodium carbonate (soda ash). Consuming the ground water supplies the calcium and magnesium levels, acidity levels. The elevated level of calcium and magnesium in water promote Ca sedimentation, resulting issues in water transmission[18].The benefits of precipitation include its effectiveness in removing heavy metals and hardness, its simplicity and cost-effectiveness for large-scale treatment, the production of stable, low-toxicity sludge, and its ability to be combined with other treatments like filtration. However, precipitation also has some disadvantages, such as the generation of sludge that requires disposal, high chemical usage which can increase operational costs, a slower process compared to advanced treatments, and the potential need for pH adjustments to optimize efficiency. Precipitation is widely used in drinking water purification, wastewater treatment, and industrial effluent management [35-39].

4.8.Reverse Osmosis (RO)

Reverse Osmosis (RO) is a water purification technique that uses a semi-permeable membrane to remove pollutants, dissolved salts, and contaminants from water (Figure 2). The process begins by passing water through pre-filters, such as sediment filters, to remove large particles like sand and dirt. Activated carbon is then used to eliminate chlorine and organic pollutants that could damage the membrane. It is a membrane based process technology to purify water by separating the dissolved solids from feed stream resulting in permeate and reject stream [15-19]. Under high pressure, water is forced through the semi-permeable membrane, which filters out dissolved salts, heavy metals, and other contaminants. Additional filtration, such as UV or carbon filters, can further improve taste and remove any remaining pollutants. The purified water is then stored in a tank for use. There are several types of Reverse Osmosis systems, including point-of-use RO systems, which are small units used in homes and offices for drinking water; point-of-entry RO systems, which are installed at the main water supply to purify all water in a building; and commercial and industrial RO systems, which are high-capacity systems used in industries, hospitals, and desalination plants. The benefits of Reverse Osmosis include its effectiveness in removing up to 99% of contaminants, including heavy metals, microorganisms, and salts, and its ability to remove chemicals like chlorine that affect the taste of water. Since the purification occurs through filtration rather than chemical treatment, no chemicals are required, and the process also reduces water hardness and scale buildup. However, there are some drawbacks, such as the production of a significant amount of wastewater (typically 3-4 liters of waste per liter of purified water), the removal of beneficial minerals like calcium and magnesium, the high cost of membranes and their regular replacement, and the time it takes to produce purified water. RO is widely used for drinking water purification, industrial applications, and seawater desalination.

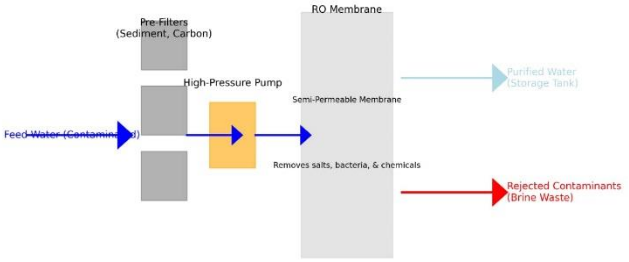

Figure 2 **Reverse Osmosis**

4.9.Ion Exchange

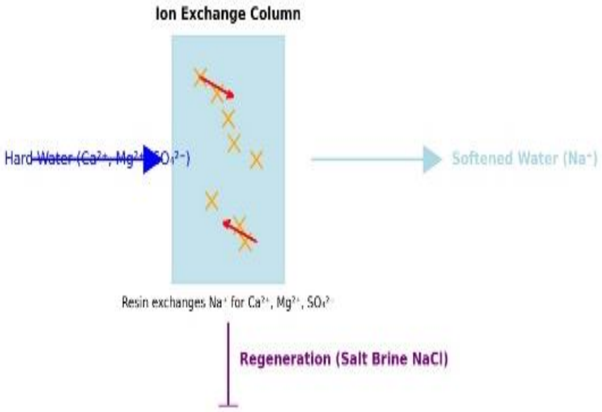

Figure 3 **Ion Exchange**

Ion exchange is a water treatment process that removes unwanted particles from groundwater by replacing them with more beneficial ones using an ion exchange resin (Figure 3). This process is commonly used to eliminate hardness (calcium and magnesium), nitrates, fluoride, and heavy metals. The process begins with resin beads that are charged with specific ions, such as sodium for softening or hydrogen for demineralization. As water passes through the resin bed, undesirable particles in the water are exchanged for the ions on the resin. Once the resin becomes saturated with unwanted particles, it is regenerated using a chemical solution, such as brine for softeners or acid/base solutions for deionization. Excess regenerant is then flushed out, and the resin is prepared for reuse. There are several types of ion exchange processes, including cation exchange, which replaces positively charged particles like calcium, magnesium, and iron; anion exchange, which replaces negatively charged particles like nitrates, sulfates, and fluorides; and mixed bed exchange, which uses both cation and anion resins in a single unit to produce high-purity water. The benefits of ion exchange include its effectiveness in removing specific contaminants like hardness, nitrates, and heavy metals, the ability to regenerate and reuse resins, making it cost-effective over time, and the production of high-quality treated water for industrial and domestic use. It is also compact and easy to operate compared to other chemical treatments. However, there are some drawbacks, such as the need for continuous regeneration, which leads to chemical use and waste disposal issues, its ineffectiveness in removing organic impurities or microorganisms (which requires additional treatment), the potential increase in sodium levels in water when using sodium-based resins, and the high initial cost for large-scale applications.

4.10. Activated Carbon Treatment

Activated carbon treatment is a commonly used method for removing organic pollutants, taste, odor, and certain chemicals from groundwater through a process called adsorption, where contaminants adhere to the porous surface of activated carbon. The process begins by filtering out large particles and sediment. Water then passes through an activated carbon filter, which can be either granular or powdered, where organic compounds, chlorine, and some heavy metals bind to the carbon surface. The filtered water may undergo further treatment, such as disinfection, if necessary. Stimulation by carbon based substance present in an environmental for the restoration of organic contaminants in the groundwater, by expectional adaptability and biological integration[23-25].There are different types of activated carbon treatment, including Granular Activated Carbon (GAC), which consists of larger particles used in fixed-bed filters for continuous flow systems and is effective for long-term filtration; Powdered Activated Carbon (PAC), which consists of fine particles added directly to water for temporary treatment and is used in batch processes; Extruded Activated Carbon (EAC), which is round and cylindrical in shape, providing high mechanical strength for high-flow applications; and Impregnated Activated Carbon, which contains added chemicals like silver for microbial control and is used for the removal of specific pollutants. The advantages of activated carbon treatment include its ability to remove organic pollutants, chlorine, and some heavy metals, as well as improving taste and odor without the need for chemicals or complex operations [26]. It is also recoverable and reusable, making it cost-effective for moderate contamination levels. However, it has some disadvantages, such as being ineffective against dissolved salts, nitrates, and certain heavy metals, and the carbon becomes saturated over time and requires replacement. Additionally, bacterial growth can occur in the filters if not properly maintained, and there can be a high initial cost for large-scale applications [27-29].

5. Biological Treatment

Activated Sludge Process (ASP), Moving Bed Biofilm Reactor (MBBR), and Sequencing Batch Reactor (SBR), The Rotating Biological Contactor (RBC) are biological treatment methods mainly used for wastewater treatment, not typically for groundwater treatment. However, if groundwater is heavily polluted and extracted for treatment, ASP, MBBR, RBC or SBR could be applied in a treatment plant setting before reuse.

5.1.Bioremediation

Bioremediation is a biological treatment method that utilizes microorganisms (microbes, growths, or plants) to separate or kill poisons in defiled conditions like soil, water, and air. It is a natural, eco-accommodating, and cost-effective strategy for natural cleanup. The cycle of bioremediation begins with recognizing the sort and degree of pollution. Once identified, local or introduced microorganisms are used to degrade the toxins. Factors like oxygen, pH, temperature, and nutrients are adjusted to facilitate the process. The microorganisms then break down impurities into innocuous products such as water and carbon dioxide. Progress is monitored to ensure complete remediation [20]. There are two main types of bioremediation: In-Situ and Ex-Situ. In-Situ bioremediation includes techniques like bioventing, where air is injected into soil to stimulate microbial degradation, and biosparging, which involves injecting air into groundwater to enhance biodegradation. Bioaugmentation adds specific organisms to accelerate the breakdown of contaminants, while natural attenuation relies on existing microorganisms for natural degradation. Ex-Situ bioremediation includes methods like biopiles, where contaminated soil is placed in piles and aerated for microbial activity; bioreactors, where contaminated water or soil is treated in controlled tanks; landfarming, which involves spreading polluted soil over a large area and aerating it; and composting, where contaminants are mixed with organic matter to enhance microbial action.The benefits of bioremediation include its use of natural processes, which reduces the need for chemicals, making it less expensive than physical or chemical treatment methods. In-situ techniques allow for cleanup without excavation, and bioremediation is effective for treating a wide range of environmental pollutants. However, there are some disadvantages. The process can take months or even years to complete, and it is less effective for dealing with heavy metals and highly toxic substances. It also requires proper oxygen, temperature, and nutrient conditions, and some breakdown products may still be harmful.

5.2.Bio Filtration

Biofiltration is a natural water treatment process that utilizes microorganisms to corrupt or eliminate pollutants from water. It is ordinarily utilized for treating groundwater, wastewater, and air toxins. The interaction of biofiltration begins when defiled groundwater passes through a biofilter media. Microorganisms attached to the media then degrade the toxins. Particulate matter is captured, and dissolved impurities are adsorbed. The treated water exits the system with reduced toxins. There are several kinds of biofiltration. The most disintegrated natural carbon(DOC) expulsion happened in the biofilters. Rapid biofilters utilized sand, anthracite, or granular enacted carbon as media with void bed contact time (EBCT)[35]. Slow sand filters use a biofilm layer (Schmutzdecke) for microbial refinement. Activated carbon biofilters employ carbon as a medium for microbial growth and adsorption. Trickling filters involve water flowing over a fixed biofilm-covered medium. Moving bed biofilm reactors (MBBR) use suspended biofilm carriers to enhance treatment efficiency. Granular media biofilters support biofilm growth with materials such as sand, rock, or other substances. The benefits of bio filtration include its effectiveness in eliminating both organic and inorganic pollutants. It is eco-friendly and sustainable, with low operational costs compared to chemical treatments. Additionally, biofiltration consumes minimal energy and can handle variable loads and shock loads. However, there are some limitations. Biofiltration is slower compared to chemical methods, and biofilm clogging can reduce its efficiency. It also requires regular maintenance and monitoring, and temperature and pH variations can impact microbial activity.

5.3.Sequencing Batch Reactor (SBR)

Sequencing Batch Reactor (SBR) is a biological wastewater treatment method that can also be used for groundwater treatment, particularly when the groundwater is contaminated and needs to be treated in an ex-situ setup. It has a higher COD expulsion productivity with a lower colour evacuation effectiveness [22].It operates in a batch process, where the system undergoes a sequence of stages within a single tank. In groundwater treatment, SBR is typically used when groundwater is pumped out for treatment in a facility, where biological degradation of contaminants, such as organic compounds or nitrates, is required. The process begins by introducing contaminated groundwater into the reactor, where aerobic or anaerobic conditions are maintained, and microorganisms break down the contaminants. Solids (sludge) settle at the bottom of the reactor, and treated water is decanted (removed) from the top. The tank is idle for a short period before the next cycle begins, and the process repeats in batches, with the reactor being emptied and refilled after each cycle. There are several types of SBR, including Conventional SBR, which uses a simple cycle for treating wastewater with standard biological processes; Extended Aeration SBR, designed for treating wastewater with higher organic loads; and Anoxic SBR, used when treating wastewater with nitrogen, such as in nitrification/denitrification processes. The advantages of SBR include its ability to handle varying influent water quality, requiring less space compared to continuous flow systems, being effective at removing organic material, nitrogen, and other contaminants, and operating at optimal energy efficiency with good aeration control. Additionally, batch operation is simple to manage and monitor. However, the system also has disadvantages, such as not being continuous, which means downtime between cycles can reduce efficiency in high-flow applications. The accumulation of sludge requires management and disposal, and careful monitoring and control of the cycles are necessary. Moreover, the system has a higher upfront cost due to its complexity.

5.4.Enhanced Aerobic or Anaerobic Biodegradation

Enhanced Aerobic or Anaerobic Biodegradation refers to the process of improving the natural microbial degradation of contaminants in groundwater by adding oxygen (for aerobic) or other electron acceptors (for anaerobic) to stimulate microbial activity. This method accelerates the breakdown of pollutants such as organic compounds, petroleum hydrocarbons, and other contaminants, making it more efficient than natural biodegradation alone. Enhanced Aerobic or Anaerobic Biodegradation is an efficient and sustainable way to treat groundwater contamination but requires careful management and monitoring to optimize conditions for microbial activity. The process of aerobic biodegradation involves adding oxygen to the groundwater to support aerobic microorganisms, which break down organic contaminants by using oxygen as an electron acceptor. Oxygen can be supplied through air injection, sparging, or mechanical aerators. Anaerobic biodegradation, on the other hand, involves creating oxygen-free conditions by adding electron acceptors like nitrate, sulfate, or carbon sources. Anaerobic microorganisms degrade pollutants in the absence of oxygen, which can be facilitated by injecting materials like lactate, acetate, or other electron donors into the groundwater. Common methods of anaerobic treatment are anaerobic digestion, upload anaerobic sludge blanket (UASB), expanded granular sludge bed (EGSB). Aerobic processes proved to be more effective in treating the organically contaminated groundwater [14]. There are two main types of enhanced biodegradation: enhanced aerobic biodegradation, ideal for contaminants like petroleum products, solvents, and other biodegradable organic compounds, where oxygen is added to promote aerobic bacteria growth; and enhanced anaerobic biodegradation, which is applied to pollutants like chlorinated solvents (e.g., TCE, PCE), which degrade more effectively under anaerobic conditions, with electron donors such as lactate or molasses added to stimulate anaerobic bacteria. The advantages of this method include being less expensive than physical or chemical treatment methods, utilizing natural processes that reduce the need for chemical interventions, and being particularly effective for degrading petroleum hydrocarbons and chlorinated compounds. Additionally, it generates minimal secondary waste and causes minimal disruption to ecosystems. However, the process can take longer to show results, especially with high contamination levels, and is not effective for all types of pollutants, particularly heavy metals or highly persistent compounds. The injection of nutrients or oxygen must be carefully controlled to avoid over-fertilizing or creating undesirable byproducts, and the effectiveness of the method depends on the site’s hydrogeology, temperature, and microbial populations, which can vary.

5.5.Constructed Wetlands (CWS)

Constructed wetlands (CWs) are designed systems that use natural processes, including wetland vegetation, soil, and microorganisms, to treat polluted water, including wastewater, stormwater, and groundwater. These systems mimic natural wetlands to remove pollutants through biological, chemical, and physical processes. Constructed wetlands provide a sustainable and eco-friendly method for water treatment, making them ideal for areas with available land and where low-cost, environmentally friendly solutions are needed. Constructed wetlands on the biggest granulometric-size of coke accomplished the best expulsions for the designated compounds (84% normal) in wastewater [11]. The process of constructed wetlands begins by removing large trash and solids before the water enters the wetland. The water then flows through a bed of gravel, sand, and wetland plants, allowing for microbial and plant-based treatment. Suspended solids settle, microorganisms break down organic matter and nutrients, and plants absorb nutrients and impurities. Heavy metals and phosphorus bind to substrate materials. The treated water exits the system, often meeting discharge or reuse standards. There are two main types of constructed wetlands: surface flow (free water surface) wetlands, where water flows above the soil surface through aquatic plants and is used for secondary or tertiary wastewater treatment, and subsurface flow wetlands, where water flows through a rock or sand bed beneath plant roots.

Subsurface flow wetlands have less odor, fewer mosquitoes, and better microorganism removal. Subsurface flow wetlands can be either even flow, where water moves laterally through the media, or vertical flow, where water moves downwards in pulses, improving oxygenation. The benefits of constructed wetlands include lower operational costs compared to traditional treatment plants, the use of natural processes reducing the need for chemicals, minimal mechanical equipment requirements, and the support of biodiversity by attracting birds, insects, and aquatic life. They can also be designed as green landscape features. However, the disadvantages of constructed wetlands include the need for significant space compared to compact treatment plants, a decrease in performance in colder climates, longer maintenance times than conventional systems, and the potential for sediment accumulation if not properly designed and maintained. Additionally, surface flow wetlands can become breeding grounds for mosquitoes if not well-maintained.

5.6.The Moving Bed Biofilm Reactor (MBBR)

The Moving Bed Biofilm Reactor (MBBR) is a biological wastewater treatment process that utilizes a suspended carrier media to support the growth of biofilms. These biofilms consist of microorganisms that help break down contaminants in the water. MBBR is typically used in both wastewater and groundwater treatment to remove organic contaminants, nitrogen, and other pollutants. The MBBR process involves water being passed through a reactor filled with plastic media that provides a surface for microorganisms to attach and form biofilms. As the water flows through the reactor, the microorganisms degrade pollutants, and the biofilm grows, making the process highly efficient in treating polluted water. The media moves within the reactor, creating continuous mixing that enhances the efficiency of the biological treatment. There are several types of MBBR systems, depending on the type of media used and the configuration of the system. These include standard MBBR systems, where the media is free to move within the reactor, and hybrid systems, which combine MBBR with other technologies like activated sludge systems to increase treatment efficiency. MBBR systems can also be adapted for specific types of contaminants, such as nitrification or denitrification processes, by selecting appropriate microbial communities and operating conditions. The advantages of MBBR in groundwater treatment include its compact design, which requires less space than traditional treatment systems, and its high efficiency in removing organic matter and nutrients like nitrogen. MBBR systems also have lower operational costs compared to other biological treatments, as they do not require the complex management of sludge, and they are easy to scale for varying water treatment demands. It is amazing in eliminating Substance Oxygen Interest(COD), All out nitrogen(TN), and complete phosphorous [4]. Additionally, the continuous movement of the media improves the contact between the microorganisms and the contaminants, making the process faster and more efficient. However, MBBR systems also have some disadvantages. They require periodic maintenance, such as cleaning and replacing the media, and can be sensitive to changes in water quality, such as fluctuations in temperature or pollutant concentration. The initial installation cost of an MBBR system can be higher compared to traditional systems, and the system may not be as effective in treating highly complex or high-strength pollutants. Despite these challenges, MBBR is an effective and versatile treatment option for groundwater, especially in applications where space and efficiency are critical.

5.7.The Rotating Biological Contactor (RBC)

The Rotating Biological Contactor (RBC) is a biological wastewater treatment process that uses a series of closely spaced, rotating discs covered with a biofilm of microorganisms to treat contaminated water [40]. It is the organic techniques which liked because of straightforward, modest, process soundness and eco-accommodating tasks and furthermore offers high interfacial region created in the turning circle to layout great contact between the microbial species and poisons [28,34]. The water is pumped into the reactor where it comes into contact with the rotating discs, which are partially submerged in the water. The biofilm on the discs consumes organic pollutants in the water as it passes through the system. The rotating motion of the discs helps improve the oxygen transfer from the air into the water, which aids the growth and activity of aerobic microorganisms that break down organic matter. In groundwater treatment, RBCs are used to remove organic contaminants and reduce nitrogen levels through nitrification. The groundwater is pumped through the system, where microorganisms attached to the rotating discs degrade pollutants. This method is effective for treating low to medium-strength contaminated water and can be used in both municipal and industrial settings. The continuous rotation of the discs provides a reliable means of mixing and aerating the water, ensuring that the biofilm on the discs remains active and efficient at removing contaminants [41]. There are different types of RBC systems, including conventional RBCs, which consist of a series of discs arranged in parallel, and advanced systems that incorporate additional components, such as secondary treatment stages or integrated filtration, to enhance performance. Some RBC systems may also be designed for specific applications, such as denitrification, by adjusting the conditions in the reactor to encourage anaerobic processes alongside the aerobic ones. The advantages of RBC systems in groundwater treatment include their relatively low energy consumption, compact design, and ease of operation. RBCs are effective at removing organic matter, nitrogen, and other pollutants from groundwater, and they require less space than other treatment methods, such as activated sludge systems. Additionally, RBC systems have a low maintenance requirement since the rotating discs are self-cleaning and do not require extensive sludge management. However, RBC systems have some drawbacks [42]. They are less efficient in treating high-strength or highly variable wastewater, and their performance can be affected by changes in the influent quality. The rotating discs may also become fouled over time, which requires regular maintenance to ensure the system's optimal performance. Furthermore, RBCs are not as effective at removing certain types of pollutants, such as heavy metals, and may need to be combined with other treatment methods for more complex contamination. Despite these limitations, RBC systems are a versatile and reliable treatment solution for groundwater, especially in cases where space and energy efficiency are key considerations.

5.8.Slow Sand Filtration (SSF) And Rapid Sand Filtration (RSF)

Slow Sand Filtration (SSF) and Rapid Sand Filtration (RSF) are two types of filtration methods used in groundwater treatment to remove impurities and improve water quality [43-45]. SSF is ideal for small-scale applications or areas with limited space and resources, while RSF is more suited for larger, industrial-scale water treatment plants that can handle faster filtration and require higher throughout. Slow Sand Filtration (SSF) involves water being passed slowly through a bed of fine sand. The filtration process includes physical, biological, and chemical mechanisms. As water moves through the sand, impurities such as bacteria, suspended solids, and organic matter are trapped and degraded by microbial activity in the biofilm layer that forms on the sand grains. SSF can be implemented using a single media filter, which uses only sand, or a dual media filter, which combines sand and a coarser material like anthracite to enhance filtration. The advantages of SSF include its simplicity, cost-effectiveness, and its effectiveness in removing pathogens and suspended solids with minimal chemical use. It also has low energy consumption due to the slow filtration speed. However, SSF requires large filter beds and significant land area, and the slow filtration rate (typically 0.1-0.3 m/h) makes it unsuitable for large-scale operations. Additionally, maintenance is required to periodically clean the biofilm layer. In consumable water treatment, low-turbidity water is often purified by direct filtration to coagulation, flocculation, and rapid sand filtration [46]. Rapid Sand Filtration (RSF), on the other hand, involves water being passed through a bed of coarser sand at a much faster rate (typically 5-15 m/h). In RSF, physical filtration is the primary mechanism for removing suspended solids, and it typically follows pre-treatment methods like coagulation and flocculation to aid in removing larger particles. RSF can be implemented using single media filters with just one layer of sand, dual media filters that combine fine sand and coarser materials like anthracite, or multi-media filters that use multiple layers of sand, gravel, and anthracite. The advantages of RSF include faster filtration rates, making it more suitable for large-scale water treatment, and a more compact design compared to SSF [47]. It can handle higher turbidities due to pre-treatment. However, RSF requires higher energy consumption and more frequent backwashing. It is also less effective at removing pathogens compared to SSF, so additional disinfection is often necessary. Furthermore, RSF comes with higher operational and maintenance costs.

Conclusion

This study confirmed the effectiveness of physical and chemical groundwater treatment technologies in enhancing water quality. Chlorination emerged as the most efficient method for microbial reduction, while coagulation proved beneficial in improving clarity and reducing TDS levels. The necessity to balance efficacy with safety in treating groundwater resource challenges was emphasized, suggesting a need for integrated treatment approaches. This study found that biological treatment methods work better than physical and chemical methods for improving groundwater quality. Biological processes, like biofiltration and bioremediation, remove harmful microbes effectively while keeping the water's natural balance. Unlike chemical treatments such as chlorination, which can create harmful byproducts, biological methods are safer and eco-friendlier. While coagulation and filtration helped make water clearer and reduced dissolved solids, they were not as effective at removing bacteria and other microorganisms. Chemical treatments worked well for killing germs but needed careful control to avoid health risks. These findings suggest that the best approach is to combine different methods, using biological treatment as the main process while adding physical or chemical steps when necessary. Future research should focus on improving biological treatments to make them more efficient and widely usable.

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