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ADVANCED WATER TREATMENT TECHNOLOGIES: LEVERAGING BIO-NANOTECHNOLOGY FOR EFFICIENT CONTAMINANT REMOVAL AND SUSTAINABLE RESOURCE MANAGEMENT

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Abstract

The essential challenge facing humanity during the twenty-first century centers on providing adequate amounts of economical and clean water for everyone. The situation grows worse because population has increased while water quality has declined alongside changing climate conditions. Nanotechnology acts as a fundamental technology enabler in integrated water operations by raising system effectiveness and permitting new water extraction methods from unconventional reserves. Nanotechnology enhances global drinking water supplies by developing innovative nanomaterials which treat surface water and groundwater and contaminated wastewater with dangerous inorganic and organic substances and harmful microorganisms and metal ions. Nanotechnology breakthroughs addressed crucial challenges within engineering physics and chemistry and other fields. The current wastewater treatment industry depends heavily on multiple products and processes derived from nanotechnology research including nano adsorbents, nano zero-valent iron, nano biocides, nanofiltration and magnetic nanoparticles and hybrid systems for wet air oxidation with nanoparticles. The review investigates recent breakthroughs in nanotechnology because it focuses on effective hazardous waste management through cost-efficient and energy-saving solutions. Different sectors including science research and healthcare along with food production have recognized both the rising value of nanotechnology and peculiar properties of nanobubbles.

Keywords: “Nanomaterials Nanotechnology”, “Wastewater Treatment”, “Artificial Intelligence”, “Nanobubble”.

1. INTRODUCTION

The global community faces a major challenge because it needs to provide accessible low-cost clean water to people whose water usage has been increasing rapidly. Population growth together with climate change along with water pollution create the greatest barriers in the operation of the water supply system. Surveys from 2014 by the WHO project that half of humanity will inhabit water-scarce areas by 2025. The global wastewater infrastructure managed proper sewage treatment of only 20% during the year 2015. The United Nations in 2016 documented that developing nations eliminate about 70% of industrial wastewater without sufficient chemical elimination. The water receives non-biodegradable substances including pathogens together with organic pollutants and heavy metals along with industrial discharge and various anions and so on. The water body undergoes characteristic changes because of these substances. The application of nanotechnology provides an efficient solution for modernizing outdated infrastructure by enabling high-cost performance and versatile and multipurpose treatment systems that can be integrated into large-scale facilities.

Traditional process engineering gains advancements toward technical processes of water and wastewater through combined usage of advanced nanotechnology. Nanotechnology researchers studied three approaches for cleaning contaminated water and wastewater through nanoscale filtration and the adsorption process using nanoparticles and the catalytic destruction with nano materials.

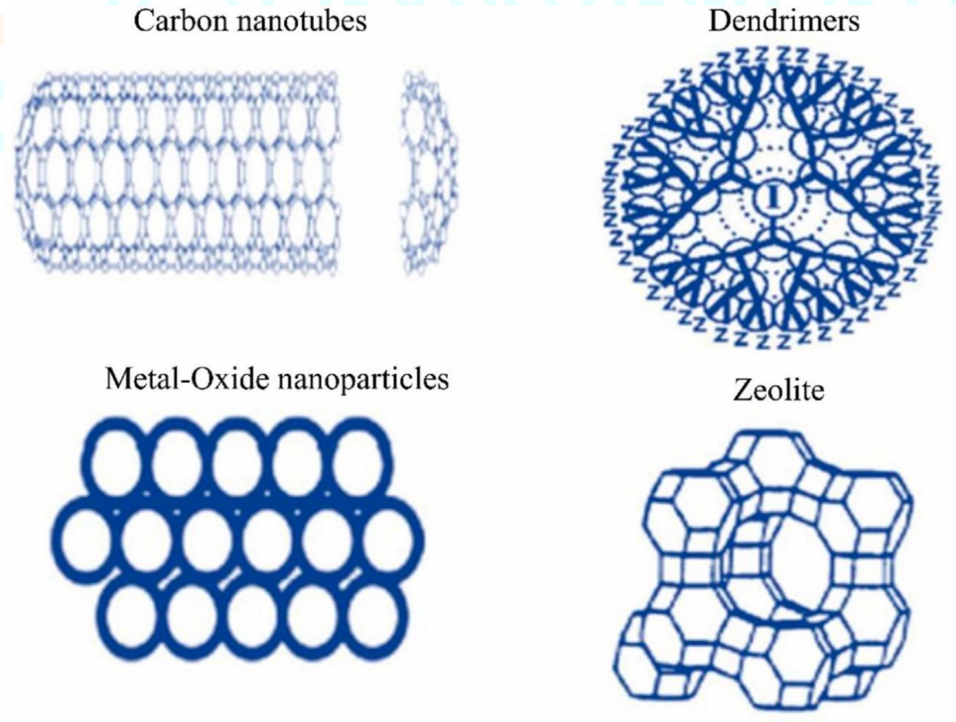

Fig 1. The zero-valent iron nanoparticle core-shell model (nZVI).

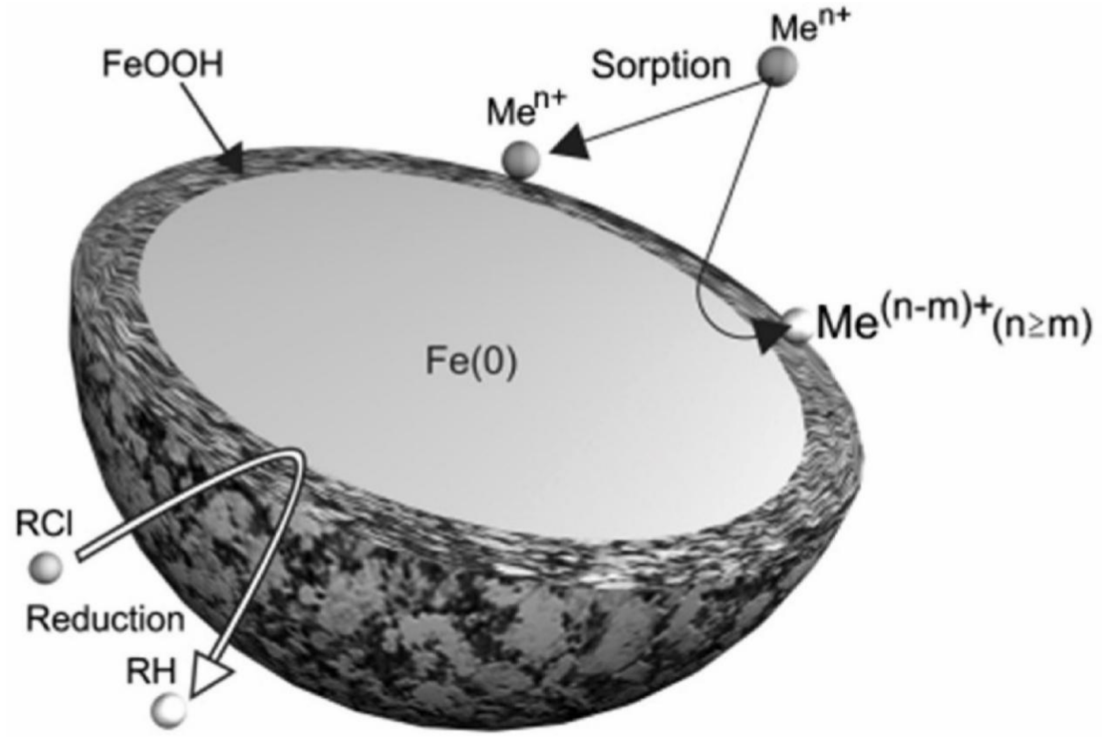

Fig 2. The zero-valent iron nanoparticle core-shell model (nZVI). The exterior is primarily made up of iron oxides and hydroxides, while the centre comprises metallic iron. Iron nanoparticles, as a consequence, display characteristics of both iron compounds and metallic iron.

The innovative field of nanotechnology demonstrates potential solutions for the current water treatment challenges. Nanotechnology enables sustainable water resource utilization which can expand the options of present water cleaning methodologies. Nanotechnology enables water treatment through three main applications which include pollution remediation alongside its purification aspect alongside surveillance functions and pollution prevention methods. Nanotechnology achieved substantial advancements as scientists mastered how to detect and understand molecular structures of pollutants through nanoparticle technology for water filtration. Nano-chemistry technologies provide better performance together with lower costs compared to traditional purification methods. The purification process employs two main approaches: membrane creation together with the utilization of mixed oxides, zeolites and bimetallic nanoparticles and carbon compounds which serve as nano catalysts for substance decomposition in water. Nano-zero valent metals together with highly paramagnetically-charged magnetic nanoparticles serve as nano sorbents which clean water through their absorbent properties. The research examines modern developments in water purification technology through nanotechnology with special focus on various nanomaterials.

The proposed nanotechnology-based wastewater and water treatment solution sets the expectation that it will resolve fundamental operational deficits in present-day treatment systems while developing new capabilities which will allow full utilization of existing water sources with economical unconventional methods. Nanomaterials show excellent chemical interaction with contaminants because of their large surface areas compared to their volumes. The application of nanotechnology improves the existing water treatment practices.

Scientists discover nanomaterials containing vast surfaces accompanied by distinctive altered properties because these materials measure between 100 nm to several nanometers in size. The development of nanotechnology has established many sustainable avenues together with water purification techniques.

The implementation of nanotechnology solutions permits water conservation and simultaneous reduction of nonrenewable energy requirements and active prevention of water and additional natural resource contamination. Preservation of ecosystems and habitats and biodiversity through this method enables future generations to meet their own requirements. It has become impractical to progress without an environmentally friendly strategy because public environmental awareness continues to grow while the usage of harmful chemicals and solvents plummets. Researchers believe advanced nanomaterials have potential to treat pollution in surface water platforms and groundwater resources as well as waste water resources and other ecological water elements contaminated by dangerous metal ions alongside metal oxides and organic and inorganic solutes and bio-organisms. A combination of five technologies serves contaminant removal: ultrafiltration membranes and reverse osmosis and carbon nanotubes and nanofiltration with nanofiber filters. The nano remediation strategy with zero-valent iron nanoparticles for groundwater removal has been implemented at big-scale cleanup sites.

METHODOLOGY

Nanoscale zero valent iron

Scientists have found many applications for nanoparticulate zero-valent iron in nitrate reduction and removal operations of soils sediments and water bodies. These nanoparticles serve dual purposes as both decontamination agents for polychlorinated biphenyls and organochlorine herbicides as well as transformation agents for these substances. Water-soluble research has shown that nanoparticles convert various organic pollutants comprising chlorinated benzenes and chlorinated alkenes and alkanes and nitro aromatics and organic dyes into safer end-products.

Using iron nanoparticles in nano remediation operations results in numerous benefits. Planetonium produced iron particles at nanometer size through reducing iron (II) and iron (III) with borohydride. The zero-valent iron nanoparticles exist between 10 and 100 nm in width. These nanomaterials contain both interior structure and surrounding outer layer. Atomic iron surface measures [Fe+2 and Fe+3] develops by iron metallic oxidation but iron metal predominates within the center. Nanoscale zero-valent iron stays popular for nano remediation because it possesses dual adsorption and reduction abilities alongside high reactive site quantity from its large surface area and many reactive sites than particles of micro dimensions. Nanoscale zero-valent iron (nZVI) represents the most thoroughly studied environment-friendly nanotechnological technique that removes pollutants from groundwater. Scientific research shows that nanometer-scale metallic iron achieves highly effective destruction of various typical pollutants which includes pesticides and dyes and trihalomethanes as well as brominated or chlorinated methanes and chlorinated benzenes and chlorinated ethenes and polychlorinated hydrocarbons. The decomposition process occurs through zerovalent iron corrosion which the environment initiates.

$$2Fe^{o} + 4H^{+} + O_2 \rightarrow 2Fe^{++} 2H_2O$$

$$Fe^{o} + 2H_2O \rightarrow Fe^{++} + H_2 + 2OH^{-}$$

The reduction of both organic and inorganic contaminant anions is possible with nZVI when used as a sorptive material. The reaction speeds of nZVI surpass conventional granular iron by many steps while showing better sorption capabilities for its design. The solution removal of Pb and Ni metals occurs through the use of nZVI technology. Metals reduce into states of lower oxidation values up to fully zerovalent. Sodium borohydride functions as the main reductive agent when it comes to producing nZVI material. A reaction occurs through mixing equal volume ratios of $FeCl3{\cdot}6H2O$ (0.05 M) solution to NaBH4 (0.2 M). The chemical process of borohydride reducing ferric iron leads to these reactions.

$$4Fe^{3+} + 3BH^{4-} + 9H_2O \rightarrow 4Fe^{o} \downarrow +3H_2BO^{3-} + 12H^{+} + 6H_2$$

Various global sites have utilized reactive barriers consisting of granular zero-valent iron for removing organic and inorganic contaminants from groundwater since many years. This technology has gained recognition as an optimal application of nZVI during recent years. Among different removal techniques this particular method stands out as the least harmful to the environment.

Scientists have achieved proper contamination treatment of aqueous solutions by using nanoscale zero-valent iron (Fe0) and bimetallic Fe0 particles as highly active reduction agents. Zhang (2003) presents an overview that details the manufacturing process along with evaluation procedures and environmental restoration functions for nanoscale Fe0 particles as well as Fe0/Ni0, Fe0/Pd0, Fe0/Ag0, Fe0/Co0, and Fe0/Pt0. The small-size particles can transform dangerous aqueous inorganic anions and various organic pollutants into more stable and safer products under aqueous conditions. The reduction of dangerous Chromium (VI) metal ions into less mobile and less hazardous Chromium (III) compounds was accomplished successfully using both Fe0 nanostructures and bimetallic Fe0 nanoparticles.

Water purification using 2D graphene

The application of 2D graphene nanoparticles for water filtration relies on pure graphene and GO and reduced GO. Nanoparticles demonstrate their effectiveness as both adsorption elements and discarding agents and photoreactive substances. Standard polyamide membranes contain thin atomic membranes which display superior filtration quality compared to graphene membranes. The use of graphene nanoparticles to achieve desalination has grown significantly popular throughout the scientific community. The outstanding performance of 2D graphene nanomaterials in water desalination stems from their strong ability to draw sodium cations. These materials accept hydrogen and nitrogen additions that deliver selective passage capabilities for cations or anions. Multiple researchers have identified microorganisms that demonstrate resistance against graphene and graphene oxide antimicrobial effects including E. coli along with S. aureus and S. mutans and the dental caries-related bacteria Pseudomonas aeruginosa. Certain research studies documented the live activity of antibacterial nanoparticles. Research shows that graphene possesses antibacterial properties based on exactly the same mechanisms outlined before which include cell physical damage alongside oxidative stress phenomena and cell membrane destabilization. Research indicates that antibacterial properties of graphene remain under dispute among scientists.

Photocatalysis

Water treatment effectiveness remains limited by the removal of non-biodegradable organic contaminants which evade standard treatment methods and have not been resolved despite disinfection method risks of hazardous by-products. The development of a novel and economic system using green technology represents the necessary solution to address these contaminant issues while consuming limited amounts of energy and chemicals. The scientific community has dedicated research to explore alternative dependable procedures named AOPs for mineralizing and oxidizing numerous organic compounds. The radical species generated by AOPs show very high potency with effective oxidizing properties. Photocatalysis functions as a well-established AOP that improves biodegradability of persistent organic contaminants while treating current and emerging microbial diseases in the environment. Photocatalytic oxidation serves as a reaction class that requires activation from light sources together with chemicals or different energy types for catalyst operation. This form of oxidation generates non-selective potent radical species including H2O2 and O2•- and O3 and hydroxyl radicals (OH•).

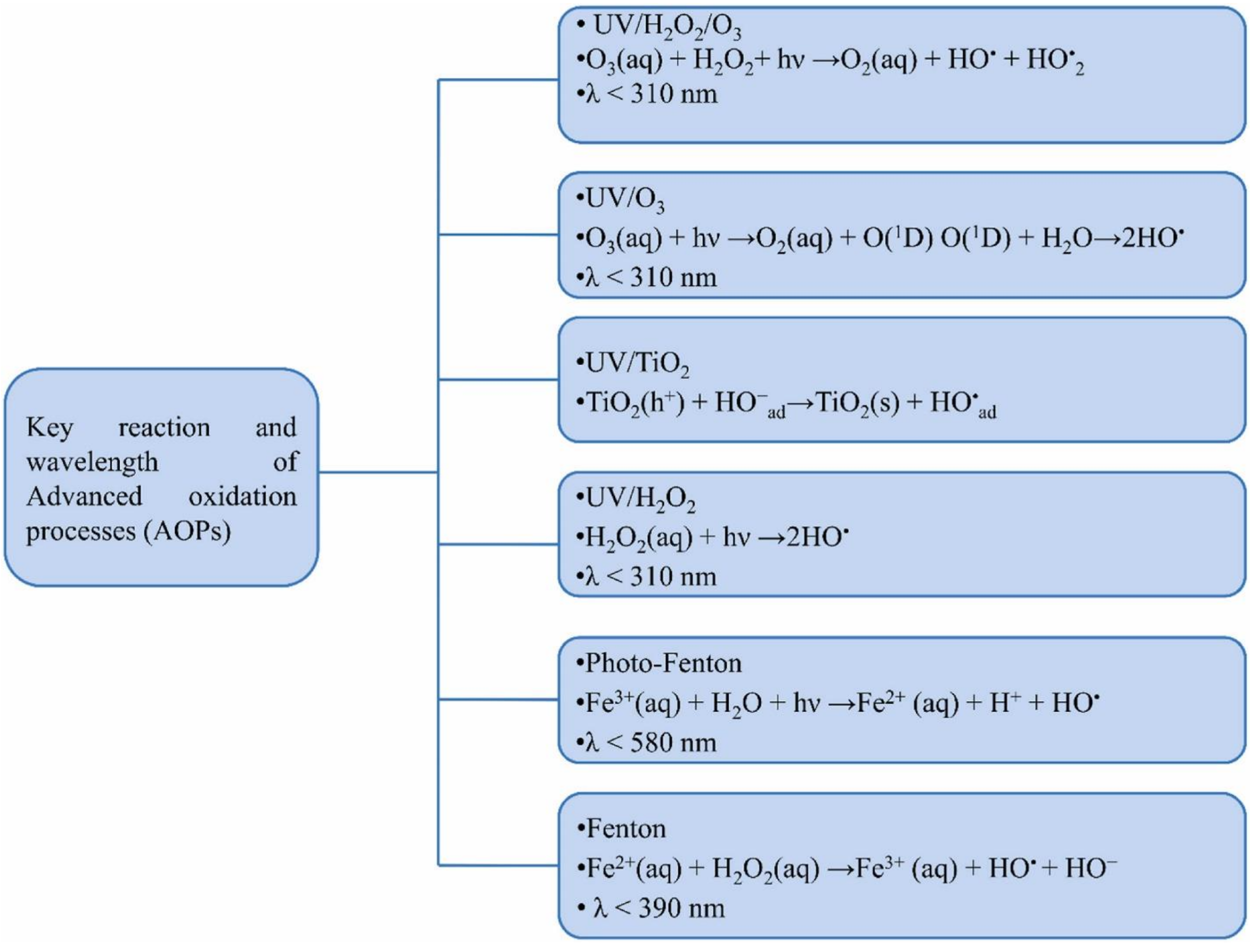

Figure 3: Metal ion recovery from aqueous solutions using improved dendrimer filtration

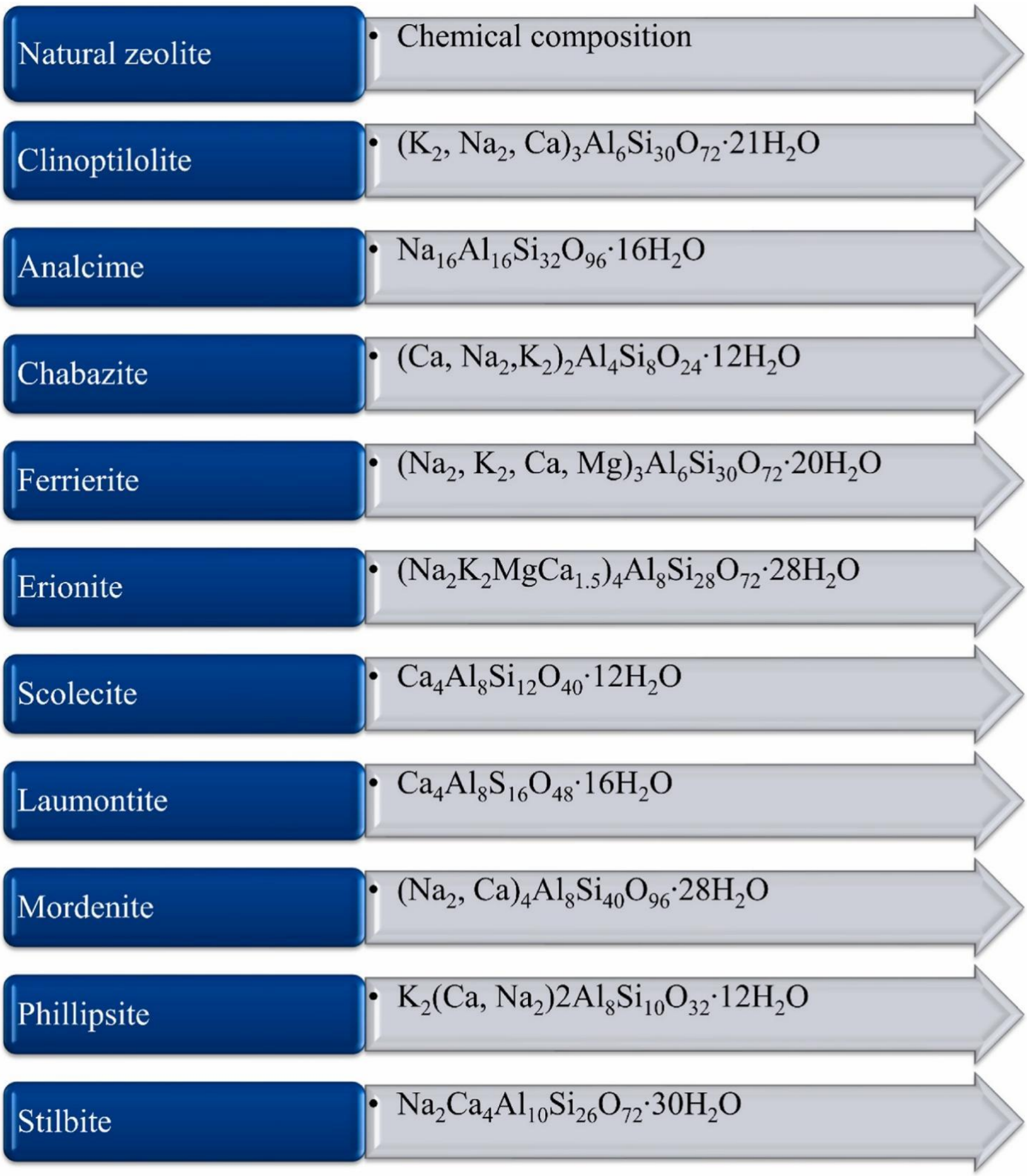

Figure 4: Illustrates AOPs that produce hydroxyl radicals through radiation

UV light or solar light irradiation together with homogeneous (photo-Fenton) and heterogeneous photocatalysis systems are both considered vital technologies. The procedure of generating photoactive iron complexes requires pH rectification but photo-Fenton photocatalysis exhibits both higher complexity in operation and increased expense in comparison to heterogeneous photocatalysis. Heterogeneous photocatalysis functions as an efficient water purification system which produces effective results in both water sterilization and persistent organic contaminants removal processes.

Various 2DM-based photocatalysts have emerged for different applications such as carbon nitride, graphene, chalcogenide nanosheets and metal oxide and researchers have categorized these materials into three pollution treatment types based on the contaminant nature.

RESULTS

Pathogen detection

Public health needs pathogen detection as it represents a critical aspect of overall health. Traditional coliform bacteria indicator systems fail to detect essential or new diseases which include Coxsackieviruses and hepatitis E, A, Norwalk viruses, adenoviruses, echoviruses in addition to Helicobacter, Legionella bacteria, Giardia and Cryptosporidium protozoa because they grow at a slow rate. Nanomaterials have become the focus of ongoing research for developing pathogen detection sensors. The sensors have three essential components including signal transduction technology and recognition agents together with nanomaterials. Waterborne detection systems based on nanomaterials achieve high sensitivity by both quick and accurate responses after a recognition event occurs. Research has applied different identification tools starting from antibodies through aptamers and polysaccharides up to antibacterial peptides. The unique physical and chemical attributes including optical power and electrochemical response and magnetic ability of nanomaterials both improve detection sensitivity while boosting efficiency at once and enabling multiple target detection. A set of tools enables users to detect differences between protein solutions and population compositions. The detection of pathogens utilizes primarily three types of nanomaterials which include Quantum dots (QDs) and CNTs and valuable metals and dye-doped NPs and magnetic NPs. Scientists have thoroughly researched both CNTs and magnetic nanoparticles for sample reduction and purification methods. The company Dynabead® produces commercial magnetic nanocomposites for developing multiple pathogen detection kits.

Trace pollutant detection

Nanomaterials serve as identifying and concentrating elements for organic or inorganic contamination traces. The environmental investigation of trace metals or organic contaminants seems promising because CNTs allow quick adsorption and fast recovery rates and rapid kinetics. Metal ions reached preconcentration factors between 20 and 300 after rapid adsorption occurred. Research on CNTs for the preconcentration of organic compounds has become extensive as it includes numerous investigations using real water samples. The process through which charged analytes connect to CNTs establishes the relationship between concentration levels and current modifications. The detection process also utilizes quantum dots together with nano-Au and similar nanoparticles. The test explored nano-Au capability to analyze pesticides at ppb concentrations through colorimetry and demonstrated its high speed and precise detection of Hg2+ and CH3Hg+. The analysis of PAH reached picomole levels per liter once researchers modified TiO2 nanotubes with quantum dots and improved detection using fluorescence resonance energy transfer. The nano sensor builds a CoTe QD surface on a glassy carbon electrode to measure very small quantities of Bisphenol A in water up to 10 nM inside 5 seconds.

Nano biocides

Membrane biofouling which arises from water-borne bacteria has developed into a primary concern that deteriorates drinking water quality. The functionalization of nanofiber surfaces has shown bacteria inhibitory effects based on several research studies. The integration of solid antibacterial and water-stable metal nanoparticles and other nano biocides has been successfully achieved in nanofiber structures. The combination of air filters and medicinal therapies includes nanofibers containing nano biocide elements. Different nano biocides fall into three categories which include fullerenes containing natural antibacterial compounds such as chitosan and antimicrobial substances with metals and metal oxides represented by nAg, ZnO, CuO, and TiO2 and nano-magnetite (nC60) and carbon nanotubes. The ultrafiltration media utilizes chitosan as an ingredient in a porous electro spun nanofibrous support that replaces the flux-limiting asymmetric permeable membrane.

DISCUSSION

Methods for purifying water using nanomaterials verses conventional methods

The upcoming decades will show worsening water problems because water scarcity will appear throughout both water-poor and water-rich regions. нових технологické řešení potřebujeme pro efektivní a levnou vodu s minimalizovaným využitím chemikálií a negativních dopadů na životní prostředí. Nanotechnology operates as a practical solution for existing and emerging water pollutants while enabling the development of seawater desalination technologies to enhance water supply.

Developmental regions along with underdeveloped nations have long relied on conventional water purification methods. The traditional procedures used for water treatment include filtration together with chemical treatment and UV radiation and desalination methods. Multiple nano-enabled devices incorporate filters and membranes composed of materials like CNTs as well as nanoporous ceramics and magnetic NPs and other nanomaterials. Traditional techniques have some shortcomings. Drinking water chlorination creates possible dangerous chlorinated product fragments which is known as a negative aspect of this process. The formation of carcinogenic byproducts from ozone and chlorine dioxide remains lower than chlorine but chlorites produced during chlorine dioxide generation cause higher acute toxicity risks. While most water facilities do not substitute chlorine with UV purification methods the technology remains unable to effectively decrease organic compounds in treated water. Drinking water purification requires microfiltration and ultrafiltration as treatments to meet the performance standards for turbidity and particle and microbial elimination. The operation of these methods needs water to undergo pretreatment procedures before activation. When disinfection by-product precursors are not properly resolved a large part of those precursors will persist in solution. The main problem with conventional water treatment using membranes is fouling.

Various AI tools are used to clean water

Numerous AI-specific tools, such as artificial neural networks as a regression model, genetic algorithms as a general optimization technique, FL as a tool for expert human decision-making, deep learning, BBNs, hybrid artificial intelligence, ANFIS, etc., have shown their broad usefulness to desalinating and treating water for a variety of purposes. Fan et al. (2018) claim that AI systems can recover energy, clean water, and materials through wastewater treatment. Reusing wastewater can enhance environmental quality while producing financial benefits and increasing water savings. The widespread use of AI techniques can be attributed to the fact that these strategies are straightforward, precise, and adaptable, producing desired outcomes.

Since AI approaches do not rely on any assumptions about ideal conditions, they are better suitable for generating models of the water treatment processes in realistic scenarios. As they focus on being predictable rather than just model fit, these strategies can be built more quickly and easily. Similarly, developing decision support systems using stochastic and AI methodologies, i.e., neural networks or fuzzy set theory, will produce acceptable methods for analyzing all such complex relationships and uncertainties. Furthermore, AI techniques can be very helpful in resolving challenging problems involving non-linear water quality data. When used to handle data at bigger sizes, these technologies are straightforward to adopt, efficient, and cost-effective, allowing policymakers to make judgments easily.

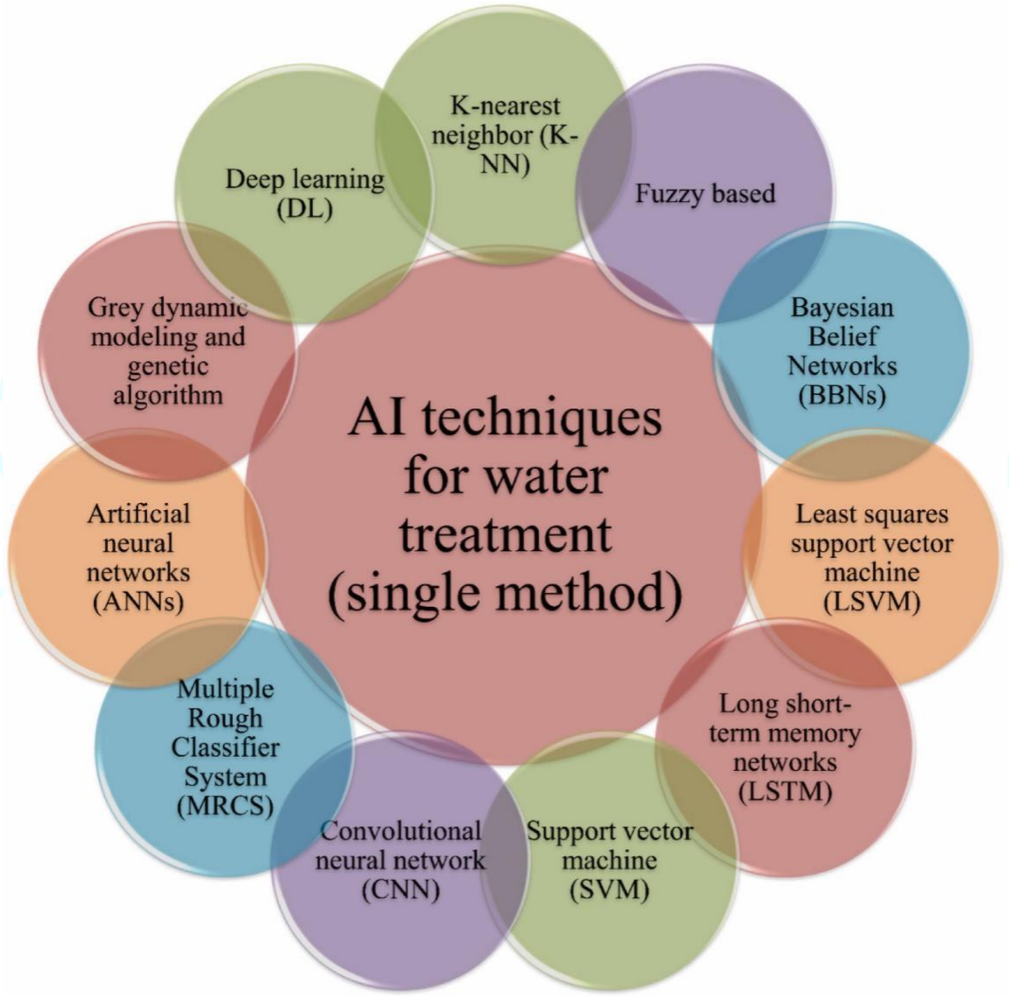

Figure 5: AI water purification using a single method

CONCLUSION

The upcoming decades will show worsening water problems because water scarcity will appear throughout both water-poor and water-rich regions. новых технологické řešení potřebujeme pro efektivní a levnou vodu s minimalizovaným využitím chemikálií a negativních dopadů na životní prostředí. Nanotechnology operates as a practical solution for existing and emerging water pollutants while enabling the development of seawater desalination technologies to enhance water supply.

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