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Original Article

Evaluation of Water Treatment Techniques Using Nanotechnology

Dr. Suresh Babu Reddy[1], Dr. Anita Verma[2]

[1]*Professor, Osmania University, India.*

[2]*Associate Professor, Banaras Hindu University, India.*

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ABSTRACT

The lack of water and its pollution has become one of the most important worldwide issues because of the high rates of human activity, urbanization, and development of industries. The traditional water treatment technology frequently has their drawbacks in efficiency, selectivity, but energy use and by eliminating new pollutants like heavy metals, pathogens, pharmaceuticals, and organic micropollutants. Over the past few years, the field of nanotechnology has got considerable popularity as an emergent technology on water and wastewater treatment due to its distinct physicochemical characteristics such as high surface area, controllable surface chemistry, increased reactivity, and increased adsorption capacity. In this paper, an in-depth discussion has been made on water treatment methods using nanotechnology, with an emphasis placed on nanomaterials carbon based nanostructures, nanoparticles based on metal and metal-oxide, nanocomposites, and nanomembranes. The paper critically examines the processes of removing contaminants, which are adsorption, photocatalysis, antimicrobial action, and membrane separation. A comprehensive literature review throws emphasis on both current developments, performance indicators, and comparative analysis of the nano-enabled treatment systems. The proposed methodology will be used to synthesize, characterise, and experimentally prove the usage of selected nanomaterials to purify water. Findings and discussion underline the efficiency of treatment, removal mechanics, scalability issues, environmental hazards and cost viability. The paper will ultimately find out some of the research gaps and future prospects of sustainable large scale application of nanotechnology based water treatment solutions.

KEYWORDS

Nanotechnology, Water Treatment, Nanomaterials, Adsorption, Photocatalysis, Nanomembranes.

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1. INTRODUCTION

1.1. Background

Clean and safe drinking water is one of the pre-requisites of a healthy human being, environmental sustainability and socio-economic development. Although the world has made major strides in terms of water infrastructure, a good number of people in the world do not have access to safe drinking water. The World Health Organization argues that false or insufficiently treated water supplies, on which billions of people in the world still evolve, contribute to the distribution of waterborne diseases and higher risks of death and health among the population. The increase in speed of industrialization, urbanization, and intensive agricultural activities have contributed to the deterioration of water quality. Industrial effluents, agricultural runoffs with pesticides and fertilizers, domestic sewages, as well as emerging pollutants such as pharmaceuticals, personal care products, and endocrine-disrupting compounds, are increasingly polluting surface water and groundwater. These pollutants are usually not only acute but also fragmentary and can occur in minute quantities, making their disappearance to be especially difficult. Traditional methods of water treatment such as the use of coagulation, sedimentation, filtration, and chlorination processes have been in use over the decades and have proven to be effective in both suspended solids and microbial virulence. Though, these ways usually fail in the challenge of such a pollutant mixture, heavy metal soluble in water, and new pollutants which needs sophisticated treatment processes. In other instances, remedial methods might in fact produce toxic by-products which again undermines the quality of water. Consequently, there is an increased demand of novel and effective treatment technologies that can resolve contemporary water pollution issues. A possible alternative is nanotechnology, which allows engineering of precise materials at nanoscale (100 nanometers to 1 nanometers), in which the phenomena of surfaces and quantum mechanics prevail. Some properties of nanomaterials at this scale include high surface area, increased activity, and control of surface chemistry, which increases the interaction with contaminants. Such properties allow better elimination efficiency, quicker treatment kinetics and lower chemical and energy usage making nanotechnology a potent means of creating next-generation water treatment solutions.

1.2. Importance of Evaluation of Water Treatment

Water treatment processes are an important part of the evaluation of drinking water and wastewater management systems in regime of effectiveness, safety and sustainability. Systematic assessment is used to identify whether treatment technologies are able to comply with the regulations and can handle the present and new water quality issues. The significance of water treatment assessment can be accepted based on the following critical points.

Fig 1 - Importance of Evaluation of Water Treatment

1.2.1. Ensuring Public Health Protection

Water treatment has its main focus of achieving the purpose of ensuring the health safety of the people by eliminating toxic contents that include pathogens, toxic metals, and chemical pollution. Constant observation of the performance of treatment will result in the fact that the water that is offered to human use is safe and does not contain microorganisms forming the diseases and dangerous substances. Waterborne diseases and chronic health hazards may arise when the treatment is ineffective, which is why constant monitoring of the performance is crucial.

1.2.2. Assessment of Treatment Efficiency

Evaluation makes it possible to quantitatively measure the contaminant removal efficiency at different conditions of operation. The reliability and strength of a treatment process can be established by examining the parameters that include the removal efficiency, kinetics of the reaction and the levels of contaminants left, which must be analyzed by the researcher, and the engineers. This is especially critical in the case of advanced technologies, e.g., nanomaterial-based systems, where it is possible that there can be fluctuations in performance with water composition and operating conditions.

1.2.3. Optimization of Operational Parameters

Critical operating parameters can be optimized using the systematic evaluation to give maximum treatment efficiency at minimum resource use including pH, contact time, temperature, dosage, etc. The optimization benefits are not only to enhance performance but also minimization of the costs of operation, energy expenditure and chemicals involved which also leads to more sustainable water treatment practices.

1.2.4. Environmental and Safety Considerations

An assessment of water treatment operations also assists in establishing the possible environmental and ecological effects such as formation of toxic by-products or secondary pollutants. In the case of emerging technologies, they need to be evaluated in order to determine material stability,

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leaching and the long-term environmental safety. This makes sure that treatment solutions do not cause any new environmental hazards in the process of eliminating the existing hazards.

1.2.5. Economic and Regulatory Compliance

The detailed assessment assists in cost-flexibility analysis and adherence of the state and international waters quality standards. Regulatory approval, large-scale implementation and widespread acceptance require consistent and effective performance manifestation. In general, systematic assessment is crucial in leading to the development of effective, efficient, and sustainable water treatment technologies that will be in a position to address the needs of future water quality.

1.3. Water Treatment Techniques Using Nanotechnology

Nanotechnology water treatment techniques have received considerable interest because of the ability to address the weaknesses of the conventional purification techniques and handle complex and emerging contaminants in an effective manner. Nanotechnology creates products and technologies that allow creating and utilizing materials on nanoscale, where surface area, reactivity, and surface chemistry can be better engineered and tuned to have an advantage in engaging with pollutants. Nanomaterials like carbon nanotubes, graphene oxide and metal or metal-oxide nanoparticles are some of the most commonly researched nanotechnology-based methods through adsorption. They have a high adsorption capacity to heavy metals, dyes, pesticides, and pharmaceutical residues and therefore, contaminants can be removed rapidly and efficiently even in low concentrations. The other significant use is in photocatalysis whereby titanium dioxide and zinc oxide nanoparticles are employed by degrading organic pollutant into harmless end products in the presence of ultraviolet or visible light. The method works well especially when treating stubborn organic contaminants which cannot be removed by the standard methods of treatment. There is also the use of nanotechnology in membrane-based systems of water treatment. Nanomembranes and nanocomposite membranes include nanoparticles into polymer scaffolds to increase permeability, selectivity and fouling degree of the membrane. These membranes are commonly applied in nanofiltration, reverse osmosis, ultrafiltration processes, which are better in removing contamination and consuming less energy. Moreover, nanoparticles that are treated with antimicrobials, including silver and copper nanoparticles, are built in the treatment system to suppress the proliferation of microorganisms and avoid biofoulling. Magnetic nanoparticles are another new concept, where separation and recovery are easily obtained upon being treated with external magnetic fields and hence enhancing re-usability and efficiency. All these nanotechnological based water treatment methods are versatile, efficient and sustainable ways of solving water quality issues in contemporary times and nanotechnology is an important enabling factor in next generation water purification systems.

2. *LITERATURE SURVEY*

2.1. Nanomaterials for Water Treatment

Nanomaterials are proven to be highly efficient in terms of water treatment because of their physicochemical characteristics such as very high ratio of surface area to volume, controllable surface chemistry and sensitivity. Nanoparticles which are commonly used include carbon nanotubes, graphene oxide, silver nanoparticles, iron oxide nanoparticles and titanium dioxide which have proven to be more efficient than the traditional bulk materials. These nanomaterials allow the effective adsorption of the heavy date metals, dyes, organic contaminants, and some of them also have high antimicrobial activity, which helps to eliminate pathogens. Their small sizes of a nanoscale make them react fast with pollutants resulting in high removals with lower material doses. Consequently, nanomaterials are found to find more applications in adsorption, disinfection, photocatalysis, and membrane based systems of water purification.

2.2. Carbon-Based Nanomaterials

Carbon-based nanomaterials, in particular carbon nanotubes (CNTs) and graphene oxide (GO), have gained massive interest in any study of water treatment processes because they have extraordinary surface area, mechanical stability, and chemical stability. NTs are hollow tubes which allow the most diverse types of contaminants to be adsorbed due to electrostatic interactions, hydrophobic forces and π– π bonding. Oxygenated graphene oxide, which has a high number of oxygen-based functional groups (hydroxyl groups and carboxyl groups) has increased affinity with the heavy metal ions and organic contaminants. In many studies, toxic metals removal by CNT- and GO-based adsorbents has been reported to be over 90 percent in terms of efficiencies. Moreover, carbon-based nanomaterials could be good solutions to developing sustainable water purification technology because of their reusability and ability to match up with composite materials.

2.3. Metal and Metal-Oxide Nanoparticles

Metallic and metal-oxide nanoparticles are essential in the high-technology water treatment, especially the breakdown of organic contaminants by photocatalysis and oxidative processes. Titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_3O_4) are some examples of nanoparticles that have been extensively studied because of their chemical stability, low toxicity and high catalysis. In particular, TiO2 nanoparticles have a high photocatalytic activity in the presence of the ultraviolet light and create reactive oxygen species that are effective to degrade organic dyes, pharmaceuticals, and pesticides into harmless by-products. Nanoparticles made of iron oxides are also appreciated due to the fact that they are easily separated and reclaimed by magnets after treatment. The properties of metal-oxide nanoparticles imply that they are very good in scalable and eco-friendly water treatment systems.

2.4. Nanocomposites

Nanocomposites are a superior type of materials that incorporate two or more nanomaterials in order to obtain synergies in enhancing performance water treatment. Nanocomposites are able to overcome the limitations of constituents, like high-poor mechanical strength or aggregation, by incorporating nanoparticles with a polymer, ceramics, or carbon-based materials. Nanocomposites based on polymers, such as, increase the membrane durability, thermal stability, selective permeability, and contaminant removal capacity is high. The adsorption capacity and antimicrobial resistance are enhanced by the addition of nanofiller using graphene oxide or metal-oxide nanoparticles. It is this multifunctional properties that allow nanocomposites to be particularly appealing to membrane filtration, adsorption and catalytic usage in water purification systems.

2.5. Nanomembranes

Membrane technologies Nanomembranes with nanomaterials have improved the process of membrane-based water filtration like nanofiltration and reverse osmosis. Introduction of nanomaterials in membrane matrices improves the permeability of water and rejection of salts, heavy metals, and organic pollutants remains high. Nanomaterials enhance hydrophilicity of membranes, reduce reconstructive Jalap by organic matter and microorganisms and enhance overall operation durability. Moreover, the antimicrobial nanoparticles incorporated into nanomembranes are used to reduce biofouling which is a significant problem in the traditional membrane systems. These enhancements result in increased efficiency, reduced energy and better sustainability thus making nanomembranes a potential remedy to solving water purification challenges faced across the world.

3.METHODOLOGY

3.1. Research Design

The research methodology in the given study is informed by a systematic experimental methodology that will test the efficiency of the identified nanomaterials in oscillating the synthetic wastewater to remove contaminants in controlled laboratory environments. Synthetic wastewater is made to give simulation of the real industrial and domestic effluents, where dissolution of heavy metals and organic contaminations are known to be in heavy concentrations with deionized water, which would maintain reproducibility and consistency among the experiments. Nanomaterials such as carbon based and the metal or metal-oxide nanoparticles are prepared or purchased in standardized forms and characterized before use to identify the makeup in terms of particle size, surface area, morphology and surface functional group. The concept of batch adsorption and degradation testing is used to determine the effectiveness of the target pollution removal using different operational parameters to best determine efficiency of the nanomaterial including but not limited to contact time, dosage of nanomaterial used, pH, and the initial concentration of the contaminant. Close monitoring of reaction conditions can be performed in the experimental setup to provide a proper evaluation of adsorption capacity, photocatalytic activity and antimicrobial performance when used. Techniques that are used to determine the quantity of residual contaminants prior to and after treatment include analytical methods like atomic absorption spectrophotometry and UV visible spectrophotometry. Nanomaterial control experiments remove the baselines and are conducted to ascertain the reliability of results. The results of the experimental tests carried out with the help of the data are statistically processed in order to determine the most preferable working regime and compare the performance of various nanomaterials. This research design will make it possible to examine the efficiency, the reproducibility and the possibility of the applicability of the nanomaterials in the water treatment processes thoroughly, in order to provide a experimental piece of strong foundation when it comes to assessing their viability in the real life of wastewater treatment process.

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3.2. Synthesis of Nanomaterials

Nanomaterials synthesis in the present case is done through chemical precipitation and sol gel method because this has been long developed to give nanoparticles with strong morphology, purity, and size distribution. In the chemical precipitation, the precursor salts of the targeted metals are dissolved in an aqueous solution and then reacted with the appropriate precipating agents under controlled reaction conditions of pH, temperature and stirring rate. The slow insoluble hydroxide or oxide precipitation permits the inspection of insoluble particles or growth reaction, a necessity to attain nanoscale measures of particles and to reduce agglomeration. Washing, filtering, and drying are then done to the precipitated nanoparticles and then followed by thermal treatment or calcination to enhance crystallinity and stability of the phases. This technique is especially appropriate when it comes to the synthesis of metal and metal-oxides nanoparticles, including iron oxide, zinc oxide, and titanium dioxide, as it is a simple, inexpensive, and scalable synthesis technique. Sol gel method is a technology that is utilized in producing nanoparticles that have a higher degree of homogeneity and structural homogeneity at the molecular level. As starting material in this process metal alkoxides or inorganic salts are utilized which are then subject to hydrolysis and condensation reaction to create a stable colloidal sol, which is then dried and calcined to yield nanoparticles characterized by well defined porosity and surface properties. The sol-gel technique provides a better ability to control particle composition and surface chemistry, which is why the sol-gel technique is especially beneficial in the preparation of photocatalytic nanomaterials and nanocomposites. This study has provided a throughway of combining chemical precipitation and sol–gel synthesis routes, which guarantee the manufacture of nanomaterials with quality uniformity, stability and ensure properties are tailored to high efficiency in the elimination of contaminants in water treatment processes.

3.3. Characterization Techniques

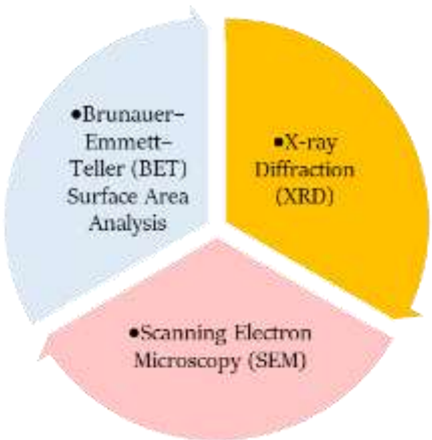

Fig 2 - Characterization Techniques

3.3.1. X-Ray Diffraction (XRD)

The X-ray Diffraction (XRD) is used to identify the crystalline structure of the synthesized nanomaterials, their composition as well as the average, crystallite size. Using the patterns of the diffraction results of the interaction of the X-rays and the crystal lattice, it is possible to detect the

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presence of a particular crystalline phase, as well as its crystallinity level. The success of the formation of the desired metal or metal-oxide nanoparticles and the presence of any impurities or secondary phases can also be determined by the XRD analysis. Also, the crystallite size is approximated through a method of peak broadening analysis that provides useful information on nanoscale sizes of the prepared materials.

3.3.2. Scanning Electron Microscopy (SEM)

The surface morphology, the shape of particles as well as the microstructural features of the nanomaterials are analyzed by scanning the Electron Microscopy (SEM). SEM offers high-resolution images that determine the distribution of particle size, texture of surface and the degree of agglomeration of nanoparticles. The method proves to be quite functional in determining the homogeneity and dispersion of nanoparticles that have a direct bearing on adsorption capacity and catalytic rate. SEM analysis can also be useful in the correlation of surface morphology to functional behavior of nanomaterial in water treatment applications.

3.3.3. Brunauer–Emmett–Teller (BET) Surface Area Analysis

The surface area analysis- Brunauer -Emmett-Teller (BET) is carried out to calculate the actual surface area of the nanomaterials and their porosity. As the adsorption efficiency highly happens to be related to the availability of surface area, BET analysis furnishes important insights as regards to the adsorption capability of synthesized nanoparticles. The method quantifies the rate of nitrogen adsorption and desorption isotherms in order to determine surface area, pore volume and distal pore size dispersion. The reason is the high surface area values used with BET as the result of analysis implies the presence of more sites where contaminants can interact, which is why nanomaterials are appropriate in the efficient water purification process.

3.4. Experimental Setup

This is because the experimental system to be applied to analyze the adsorption performance of the selected nanomaterials in this study is aimed at systematically assessing the adsorption efficiency of the selected nanomaterials in controlled laboratory conditions through batch adsorption experiments. Analytical-grade chemicals and deionized water are used to prepare synthetic wastewater with known concentrations of target contaminants in order to provide consistency and reproducibility. Certain weight of synthesized nanomaterial is then under the pre-known weight of the solution in fixed volumes of the wastewater into conical flasks or reaction vessels, and then put on a temperature controlled orbital shaker to ensure a constant amount of mixing during the experiment. The pH of the solution is brought to a preset level with the dilute hydrochloric acid or sodium hydroxide solutions and kept constant since the pH is a decisive factor in determining surface charge, adsorption capacity and speciation of contaminants. To investigate the influence of temperature on the adsorption kinetics and adsorption equilibrium, temperature is held at the required conditions with a thermostatic water bath or incubator. Contact time is also varied systematically by taking out samples at fixed periods to evaluate the rate of contaminants removal and establish equilibrium levels. The nanomaterials are filtered or centrifuged at the conclusion of every experimental run to eliminate

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interference during the analysis procedure of the treated water. Parallel control experiments involving non-nanomaterials are also done to take care of any organophosphate degradation or adsorption. Appropriate analytical methods like the atomic absorption spectroscopy or UV -visible spectrophotometry are then used to analyze the remaining concentrations of contaminants in the supernatant. All the experiments are repeated three times to make the results accurate and reproducible. It is a controlled batch-type experiment that provides the ability to examine the effects of pH, temperature, and contact time and dosage of adsorbents on the ability to remove contaminants reliably, which can then offer fundamental information on the ways adsorption works, and on how to operate the process with different conditions of operation, which can be useful in targeting large-scale water treatment in the future.

3.5. Adsorption Kinetics and Isotherms

Adsorption kinetics and equilibrium isotherm models are used systematically to analyze the adsorption behavior of contaminants onto the synthesized nanomaterials so as to understand the nature of adsorption mechanisms and the nature of their interactions. The data on equilibrium collected by batch adsorption experiment is evaluated on the basis of the Langmuir and the Freundlich isotherm models, which are some of the most commonly used models in adsorption research. The Langmuir isotherm equation is founded on the principle that adsorption is proceeded homogenously on a homogeneous surface having a limited number of identical adsorption sites resulting in a monolayer coating of the adsorbate. In this model the equilibrium adsorption capacity takes the form of a relationship of the maximum adsorption capacity of the nanomaterial, Langmuir constant regarding adsorption affinity, and the equilibrium concentration of the contaminant in solution. The Langmuir model is especially helpful in assessing the maximum uptake capacity and forecasting the adsorption process at concentrations of contaminants that are at higher concentrations. Freundlich isotherm on the other hand is an empirical model, which assumes that adsorption takes place on a heterogeneous surface having different adsorption energies. The equilibrium adsorption capacity in this case is corresponding to Freundlich constant that reflects adsorption capacity and an intensity parameter that reflects adsorption favorability. Freundlich model is better applicable in explaining multilayer adsorption and adsorption on non-uniform surfaces. The adsorption properties of the nanomaterials are fully evaluated by fitting the experimental data to the two models. The equilibrium adsorption capacity is the number of contaminants that were adsorbed per unit mass of nanomaterial whereas the equilibrium concentration is the amount of contaminant that was still left in the solution after adsorption equilibrium was reached. A comparative study of these isotherm models can identify the exploring mechanisms of adsorption and would help a lot in improving the optimization of the water treatment system using nanomaterial.

4.RESULT AND DISCUSSION

4.1. Removal Efficiency Analysis

As it is seen in the removal efficiency analysis, iron oxide nanoparticles undergo extremely good performance regarding removing heavy metals in synthetic wastewater, and based on experimental data, a removal efficiency of over 95 percent can be obtained under optimal settings. This

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efficiency can be explained by the peculiarities of physicochemical properties of the iron oxide nanoparticles, such as a significant specific surface area, having a high density of active adsorption sites, and high affinity to metal ions. The binding of metal ions to surface of the iron oxide nanoparticles is done by functional groups of hydroxyl on the surface which help in binding the ions via electrostatic interactions, surface complexation, and exchange of ions. Consequently, heavy metal elements like lead, cadmium and chromium will be trapped successfully on the surface of the nanoparticle, which will immensely limit their content in the treated water. The outcomes of the experiment also indicate that operational conditions, including the pH level, the duration of contact, and the dosage of the nanoparticles, have a significant effect on the efficiency of removal. The removal is generally most effective under near-neutral PH conditions, and in which the nanoparticles and the metal ions have been in contact with each other the most. The higher the contact time, the more the rapid initial adsorption process and slower approach to equilibrium giving an indication of efficient transfer of the mass and high adsorption affinity. Also, the increase in nanoparticle dose will lead to an availability of more adsorption sites which are beneficial in enhancing the performance of metal removal. The consistency of findings on various experimental runs demonstrates the predictability and conservativeness of iron oxide nanoparticles concerning their use as efficient adsorbents. Moreover, the ease of separation and recovery of iron oxide nanoparticle and use of external magnetic fields after treatment make their magnetic properties to increase the practical applicability and reusability. In general, the analysis of the removal efficiency demonstrates that iron oxide nanoparticles have the potential of being highly efficient, economical and eco-friendly materials to use in the treatment of heavy metals in water treatment.

4.2. Effect of Ph and Contact Time

The performance of nanomaterials in adsorption depends on the pH and contact time, which is a factor that is highly important in defining the general efficiency of heavy metal adsorbent in the wastewater. Experimental findings have shown that the best adsorption is at neutral pH levels to mildly alkaline pH levels and is normally in the range of pH 6.5 to 8.5. The adsorption efficiency is less at lower pH because of the enhanced competition of hydrogen ions with metal ions to adsorption sites on the surface of the nanomaterial. The surplus hydrogen ions also cause protonation of functional groups on the surface which causes electrostatic repulsion of the positively charged surface and cationic metal. An increase in pH to non-acidic and slightly alkaline conditions leads to the deprotonation of the surface functional groups to form negatively charged sites that helps in an increase in electrostatic attraction and complexation of metal ions, leading to an increase in adsorption efficiency. Another parameter that has an effect on the adsorption process is the contact time. The experimental findings indicate that the adsorption of the heavy metal ions is quick in the first stages of the adsorption process due to the high number of active adsorption sites on the surface of the nanomaterials. This is a rapid adsorption step at which the rate of adsorption decreases gradually as the adsorption sites get increasingly occupied. The equilibrium is reached in about 60 minutes in which the adsorption process is quite fast and efficient. At a point past this equilibrium time, a value of zero adsorption capacity is no longer observed and this indicates the occupation of available binding sites. The brief balance period demonstrates the practical feasibility of the nanomaterials in the real-time

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water treatment operations. On the whole, a synthesis of pH and contact time analysis proves that it is possible to maximize adsorption performance by working with neutral to slightly alkaline conditions and sufficient a contact time.

4.3. Comparative Performance Evaluation

Table 1: Comparative Performance Evaluation

Nanomaterial	Removal Efficiency (%)
Graphene Oxide	96
TiO_2	92
Fe_3O_4	94

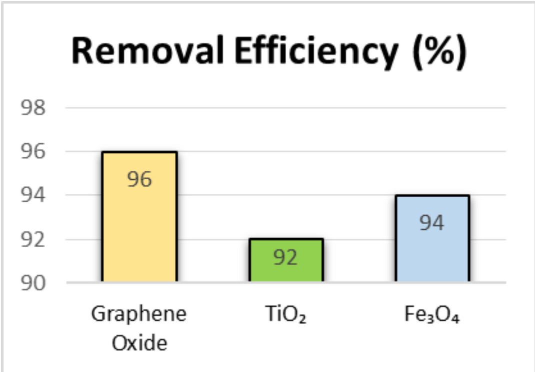

Fig 3 - Comparative Performance Evaluation

4.3.1. Graphene Oxide

Graphene oxide has the highest removal efficiency of all the investigated nanomaterials, and the removal rate is 96%. Such high performance is mainly due to its high specific surface area as well as the high number of oxygen containing functional groups (hydroxyl, epoxy, and carboxyl groups). These functional groups serve as numerous active sites which can be adsorbed and interact strongly with contaminants by an electrostatic attraction mechanism and surface complexation. The ability of the graphene oxide to be accessed through its various layers is also useful in improving the availability of the adsorption sites and therefore is very effective in the process of water purification.

4.3.2. Titanium Dioxide (TiO_2)

The removal efficiency of titanium dioxide is shown to be of 92 indicate that titanium dioxide has a high potential of application as a multifunctional material in water treatment processes. The adsorption capacity of TiO 2 is relatively lower than that of graphene oxide, however, this material has been highly achieved due to the presence of photocatalytic properties, thus allowing it to degrade organic contaminants when exposed to the ultraviolet light. Its stability with respect to chemical, non-toxic and corrosibility are some of the reasons why it exhibits consistency in its performance even with repeated cycles of use. These properties render TiO 2 to be especially convenient to be applied to the combined adsorption and photocatalytic treatment.

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4.3.3. Iron Oxide (Fe_3O_4)

The iron oxide nanoparticles have a removal efficiency of 94, which means that it has good adsorption ability with the contaminant of water. Fe_3O_4 is a high-performing material because it has high affinity with the metal ions and also there are groups of hydroxyl on its surface which facilitate the process of adsorption in terms of ion exchange and complexation. Also, since iron oxide is magnetic, it can be easily separated and recovered following the treatment and this increases the operational efficiency and reusability. The combination of low removal efficiency and convenient handling properties makes Fe_3O_4 a prospective compound to be used in large-scale water treatment processes.

4.4. Environmental and Health Considerations

Although nanomaterials have considerable benefits in the process of water treatment, their possible effect on the environment and health should be taken into consideration in order to make their use safe and sustainable. Leaching of nanoparticles to treated water bodies is one of the main issues that are linked to the application of nanomaterial based treatment systems. Released nanoparticles can also be retained in the water bodies due to their extreme small size and high mobility, and may be absorbed by living organisms where they may accumulate in the biological systems. This may be dangerous to human health and aquatic ecosystems in terms of oxidative stress, cellular damage and disruption of biological functioning. As such, it is important to determine what happens to the nanoparticles, how they are transported and the character of nanoparticles existing in water systems. Another factor of interest is toxicity especially in the case of metal and metal-oxide nanoparticles which could present cytotoxic or genotoxic activities based on the composition, size, surface chemistry, and the concentration. The result may be the negative impact of prolonged or uncontrolled exposure of the microbial communities in the natural water purification process and wastewater treatment system to some nanoparticles. In order to reduce such risks, it is necessary to have the proper immobilization strategies. Nanoparltings may be incorporated into stable materials, e.g. nanocomposites with polymers, or implanted in membranes, which can greatly decrease the chances of releasing nanoparticles and at same time achieve effective treatment efficiency. Also recovery and reuse technologies, e.g., magnetic separation of iron oxide nanoparticles are an important part of reducing environmental exposure.There should also be development of regulatory frameworks and risk assessment procedures in line with technological advancement to achieve responsible implementations. The environmental impact of nanomaterial-based water treatment systems has to be measured by life cycle assessment and the evaluation of toxicity with time. With these concerns on the environment and health issues being considered through proper design, immobilization, recovery and regulation of nanotechnology the nanotechnology can be utilized safely in offering effective and sustainable solutions to the problem of treating water world-wide.

4.5. Economic Feasibility

The economic viability of nanomaterial-based water treatment technologies is one of the critical determinants of their massive application and business viability. Though the capital cost, which pertains to the synthesis, processing, and incorporation of the nanomaterials, is relatively high with regards to the traditional treatment materials, the benefits in terms of operational performance in the long-term contributes greatly to the overall cost-effectiveness of the same. High adsorption capacity, catalytic efficiency, and durability of the advanced nanomaterials also lead to a decrease in the amount of material needed to conduct an effective treatment process as well as the increase in operations lifetime. This will cause the decreased replacement frequency and the decreased maintenance expense in the long run which will compensate the increased initial expense. A primary significant economic benefit of systems based on nanomaterials is that they render lesser use of chemicals in treating water. Traditional practices tend to be largely dependent on chemical coagulants, disinfectants, and oxidizing agents, which factor to on repetitious operating expenses as well as subsequent pollution. However, nanomaterials have the potential to operate effectively in adsorption, photocatalysis or membrane filtration with a small amount of chemical additives. Moreover, the reusability and regeneration possibilities of a number of nanomaterials also increase the economic performance. As an illustration, magnetic nanoparticles are easily recyclable and can be reused several times without strong degradation of its efficiency, which cuts on the amount of materials used and the cost of waste disposal. Economic feasibility is also facilitated by saving of energy. Nanomaterials can be used to improve the permeability and reduce fouling in membranes, as nanomaterials have a higher permeability and low fouling. Upon comparison via life cycle cost analysis, the concepts of nanomaterial-based water treatment systems have a competitive or potentially better economic performance in comparison with standard technologies. Nanotechnology is likely to be a more cost-effective and sustainable approach to water treatment in application in the future as the cost of materials ever-decreases due to advances in synthesis methods and large-scale production.

5. CONCLUSION

Nanotechnology is a very promising and efficient method which can be used in dealing with the increasing challenges of sophisticated water treatment uses. Nano enabled material in water purification systems has proved to be very effective in comparison with the traditional water purification modes especially in the removal of contaminants in the water, the capacity of adsorption, reaction kinetics and selectivity of a large percentage of various pollutants. Carbon-based nanostructures, metal and metal-oxide nanoparticles, nanocomposites, and nanomembranes are the nanomaterials that possess special physicochemical characteristics, including high surface area, surface chemistry that can be easily regulated, and high reactivity that allows them to remove heavy metals, organic pollutants and pathogenic microorganisms. These benefits permit quicker necessary treatment procedures, decreased material consumption and enhanced effectiveness of the system, in general. In spite of these obvious advantages, there are a number of issues that need to be resolved before the implementation of nanotechnology-based water treatment systems can become a common practice on industrial levels. Scalability has also been of central interest in that laboratory-scaled synthesis and deployment of nanomaterial may not necessarily scale up to large scale manufacturing at cost-effective levels. Also, there will be a need to carefully evaluate the potential environmental and health hazards of nanoparticle release, persistence, and toxicity. Nanomaterials have not been well understood regarding its long-term dynamics in water and its interactions with living organisms and hence requires a thorough risk evaluation and regulation. Economics is also a major factor since the cost of

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making nanomaterials and integrating systems are initial costs that are quite expensive, but they can be compensated by the high energy efficiency of operation over time, decreased chemical usage, and enhanced life cycles. In order to make the use of nanotechnology in the treatment of water sustainable and safe, future researches should dwell on a number of areas. Comparison of the life-cycle assessment studies is necessary to determine the total environmental footprint of nano-enabled treatment systems during the process of manufacturing a material up to its disposal. Complex toxicity tests and ecology impact analysis are required to determine the safe limit of operation and to reduce the unintended environmental impacts. Additionally, the pilot studies and field experiments on a large scale must take place in order to verify the laboratory results in the field and determine the long-term performance, stability and cost-benefit. With further research, innovation, and responsible design, nanotechnological-based water treatment system can be used transformatively in the future to achieve safe, efficient, and sustainable water solutions to the generations to come.

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