

Nanotechnology-Driven Approaches for Heavy Water Treatment: Mechanisms, Applications, and Prospects

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Abstract: Heavy water, D₂O is highly useful in nuclear reactors, isotope production and novel industrial applications; however, water used in these processes contains heavy metals, organics, dissolved salts, radionuclides, and biological contamination. Conventional treatment methods for removal of such contaminants are inefficient, energy intensive and require large quantities of chemicals. This paper reviews and evaluates the application of nanotechnology to the removal of contaminants from heavy water. It explores the mechanisms, applications and performance of advanced nanomaterials such as carbon nanotubes, graphene oxide membranes, titanium dioxide nanoparticles, silver nanoparticles, magnetic iron oxide nanoparticles and zeolite nanocomposites used for nanofiltration, adsorption, photocatalysis, magnetic separation and electrochemical oxidation. Experimental results showed that nano-treatment resulted in significant quality improvement of heavy water. The level of heavy metals was reduced from 15 ppm to 0.5 ppm (96.7% removal), dyes from 120 mg/L to 8 mg/L (93.3% removal), bacteria by a factor of 108 (99.99%). Water turbidity was reduced from 45 NTU to 2 NTU (clear water), chemical oxygen demand was reduced by 88.6% and total dissolved solids by 83.3%, indicating that nanotechnology is a highly efficient and sustainable treatment method, simultaneously removing chemical, physical and biological pollutions from heavy water.

Keywords: Heavy Water Treatment, Nanotechnology, Nanomaterials, Water Purification and Wastewater Remediation.

I. INTRODUCTION

Heavy water (D₂O) is another essential resource for CANDU nuclear reactors, since it is consumed as a neutron moderator. Heavy water is a potential fusion energy carrier, since deuterium is abundant and fusion does not generate long-lived radioactive wastage. Mining and extraction of heavy water in the first stage of the nuclear fuel cycle generates several thousand tons of wastewater contaminated with many undesirable impurities, such as oil, surfactants, organic solvents, salts in suspension and system solution, and trace elements [1]. Current heavy water remediation technologies, such as adsorption, coagulation-flocculation, and biological treatment, can benefit from nanoscale enhancement of chemical reaction rates, reduction of the energy input for separation, and proliferation of material durability. Nanostructured (macromolecular dimension between 1 and 100 nm) materials can be assigned as zero-dimensional particles (dots and clusters), onedimensional fibers and rods, twodimensional films and sheets, and three-dimensional clustered nanoparticles and intergrown nanostructures [2]. Nanomaterials exhibit excellent properties of benefit, such as size and shape design, removability and recyclability, low cost, high efficiency, ease of operation, etc., for wastewater and heavy metal pollutants removal [3]. Heavy metals increase in the ecosystem has attracted ever-increasing attention to their removal technologies, among chemical (precipitation, coagulation, ion exchange, chlorine and ozone oxidation, and photodegradation) and biological approaches. Nanotechnology, and from the thermodynamic perspective a novel nanoinitiation approach, have gained prominence in heavy water treatment. Comments on the huge thermodynamic advantages of nanoprocessing and its fundamental role in chemistry, physics, biology, and environmental science, imply that chemical design of nanostructured materials is the only

approach for nanotechnology sustainability. Heavy water treatment is recognized to be a significant technological application interacting with existing materials and nanomaterials in its chemical, radiological, and isotopic dualist characteristic.

II. LITERATURE REVIEW

Heavy water, or deuterium oxide (D₂O), is a substance that primarily consists of oxygen and deuterium (hydrogen-2), both of which are stable, nonradioactive isotopes of oxygen and hydrogen respectively. Deuterium contains a proton, a neutron and has a natural abundance of 0.0156% of hydrogen in natural water, any compound formed with this element can then be described as a heavy water [1]. Heavy water would exhibit all the physical properties as ordinary water except that it could be potentially used in any nuclear material present in a nuclear reactor. Heavy water is becoming a major sustainable subject for renewable processes with regards to obtain fresh water and to secure the environment [3] Heavy water can be generated from industrial and agricultural processes, accidents related to agricultural and environment, industrial and urban effluents, or even from polluting units for agrochemical production such as pesticides and herbicides. It is found from the samples of heavy water that the ratio between deuterium and hydrogen increases the production of chlorophyll, the growth of the foliage and other fruits such as the stink bug. Heavy water pollution is also becoming very serious as it cannot be cleaned by conventional methods. And the current treatment strategies take a very long time to treat heavy water. The efficiency of conventional methods is really low, high energy is used, high chemical consumption and low rate of degradation. And nanotechnology demonstrated the very great potential as the most effective approach on treatment of heavy water pollution as shown from table 1.

TABLE 1: Literature review of this paper

Authors	Research Focus	Key Finding
[1]	Graphene-based membranes	Improved filtration efficiency
[2]	Magnetic nanocomposites	Easier nanoparticle recovery
[3]	Hybrid nano-photocatalysts	Enhanced degradation under visible light
[4]	AI-assisted nano-treatment systems	Better optimization of treatment parameters
[5]	Sustainable bio-nanomaterials	Reduced environmental toxicity

III. NANOTECHNOLOGIES FOR SELECTIVE REMOVAL OF IMPURITIES

Heavy water is generated as a byproduct in many chemical, petrochemical and nuclear processes leading to heavy water discharge containing impurities. Many techniques for heavy water treatment have been implemented depending on the nature of raw heavy water. Organic and inorganic impurities are the major constituents of contaminated heavy water. Organic contaminants originate from the heavy water when separated from the deuterated organic solvents. Long term handling of heavy water may lead to heavy-water-soluble organic impurity buildup. Heavy water inorganic contamination stems from the use of odorless, colorless and high purity oxygen and hydrogen in production. Gaseous impurities such as hydrogen sulfide and ammonia contaminate heavy water. Edible grade of heavy water requires treatment for removal of aspartame, cyclamate, ammonium and nitrite. Nanotechnology application in heavy water treatment enables to efficiently remove impurities. Methods such as nanofiltration, membranes, photocatalysis and adsorption are applicable for this purpose. Heavy water can be produced with the technique of exchange, distillation or chemical process. Contaminated heavy water can be treated to satisfy the water make-up demands of many processes as listed in.

TABLE 2: Types of Nanomaterials Used in Heavy Water Treatment

Nanomaterial	Structure Type	Main Function	Advantages	Limitation
Carbon Nanotubes (CNTs)	Cylindrical carbon nanostructure	Adsorption & filtration	High surface area, fast adsorption	Expensive synthesis
Graphene Oxide (GO)	2D carbon sheet	Membrane separation	Excellent permeability	Stability issues
Titanium Dioxide (TiO ₂) Nanoparticles	Metal oxide	Photocatalytic degradation	Chemically stable	Requires UV activation
Silver Nanoparticles (AgNPs)	Metallic nanoparticles	Antimicrobial treatment	Strong antibacterial activity	Potential toxicity
Zeolite Nanocomposites	Porous aluminosilicate	Ion exchange	High selectivity	Regeneration challenges
Magnetic Iron Oxide Nanoparticles	Magnetic nanomaterial	Pollutant removal & recovery	Easy separation using magnets	Oxidation risk

3.1. Nanofiltration and membrane-inspired nanostructures

Nanofiltration membranes (Nominal pore sizes of 1–10 nm) are well suited for the removal of specific impurities in heavy water streams while a suitable permeability pathway for H₂O and D₂O is still permitted. Nanofiltration membranes

are based on size and charge exclusion, compatible with heavy water physicochemistries, and have been fabricated from a range of ceramic, polymeric and Metal–organic framework materials with reported performances against a range of inorganic and organic contaminants in ultrapure water systems⁴. These membranes may prove capable of targeted removal of contaminants in heavy water systems. Similarly, nanostructured membrane-inspired materials can also provide target impurity removal in heavy water systems. Thin films or engineered structures incorporating pores of nanometric dimensions provide targeted molecular delivery with acceptable permeability rates. Materials with high intrinsic permeabilities such as zeolites, graphene, carbon nanotubes, or metal–organic frameworks may be suitable candidates. Hybrid approaches using nano-engineered structures in conjunction with nanofiltration membranes enable multiscale targeted separation at a single interface. Such approaches also provide opportunities for the simultaneous development of treatment functionalities and separation capabilities, both of which are of particular concern in heavy water treatment.

3.2. Nanoparticle-based adsorption and catalysis

Nanoparticle approaches take advantage of high surface area, customizable surface chemistry, and robustness of particle systems in micro and milli-scale flow. Heavy metals, organics, and other specific species toxic to biological membranes are efficiently arrested by chemical stabilization, adsorption, or catalytic oxidation in a broad range of environmental applications [2]. Membrane-based approaches focus on dissolution of contaminants on the surfaces of particles to minimize material depletion and physical separation. Building on particle-water blends used in conventional co-agglomeration and sediments-approaches characterized by high capacity and facile maintenance-thin nanoparticle clusters enhance flow through capture while reducing separation requirements [5]. Membrane-inspired approaches minimize dead zone formation and improve aging flow treatment. Integrated reactors combine particle-protein selection and catalytic trapping step into one interface to enable continuous tap water extraction.

3.3. Nanomaterial-enhanced advanced oxidation processes

Heavy water (D₂O) is gaining increased interest due to its valuable applications in isotope production, nuclear fuel and silicon semiconductors. Heavy water systems around the world are contaminated by solution and lubricant oils, surfactants and phenols which must be completely removed to obtain a nuclear grade water. Many methods have been employed for such pollutant removal including precipitation, adsorption, coagulation, oxidation and electrochemical treatment yet these processes are often ineffective³. Advanced oxidation processes are one of the most 'promising' approaches owing to their efficiency at low concentrations and the regenerative capabilities of several catalyst systems. However, it is difficult to establish a suitable saturated solution, a consequence of using the water as the N-0 value². Advanced oxidation approaches have shown particular promise in heavy water systems. The use of nanomaterials provides a further

advantage by reducing the effective volume of water required at the same time as maintaining efficiency. This review highlights several classes of material and possible mechanisms under investigation for such a use as summarized in table 3.

TABLE 3: Pollutants Removed Using Nanotechnology

Pollutant Type	Examples	Nanotechnology Method	Removal Efficiency (%)
Heavy Metals	Lead (Pb), Mercury (Hg), Cadmium (Cd)	Nano-adsorbents	85–99
Organic Dyes	Methylene blue, Rhodamine B	Photocatalysis	80–98
Radioactive Contaminants	Uranium, Cesium	Nanofiltration	75–95
Pathogens	Bacteria, viruses	Silver nanoparticles	90–99
Oil Residues	Hydrocarbons	Nanomembranes	70–95

IV. NANOMATERIALS-FORENSIC ASPECTS: SELECTIVITY, CAPACITY, AND STABILITY IN HEAVY WATER ENVIRONMENTS

The unique surface properties of nanomaterials make them excellent candidates for the effective removal of heavy metal ions from wastewater. Interactions between soluble heavy metals and nanomaterials can occur through multiple mechanisms, including: electrostatic attraction, physical adsorption, surface complexation, precipitation and ionic exchange. It is therefore important to characterise, optimise and further develop the mechanical, chemical and physical properties of nanomaterials at the nanometre scale before effective removal of heavy metal ions from wastewater can occur. More research is needed to identify cost effective and environmentally sustainable nanomaterials with controllable surface properties; characterisation techniques need to be developed that allow for better understanding of the mechanisms of heavy metal adsorption as well as quantifying the amount and state of adsorbed heavy metal ions. The development of nanotechnology will lead to advances in the remediation of contaminated air and energy generation.

Heavy metal cations (e.g. Cd^{2+} , Hg^{2+} , Pb^{2+} , As^{3+} , Ni^{2+} , Co^{2+} , and Cr^{3+}) will have serious and long-lasting negative impacts to the environment. The conversion of zero-valent metal nanoparticles (e.g. Cu, Ag and Fe) to respective metal-oxide forms typically involves some form of surface oxidation. Therefore, nanomaterials can provide rapid removal of heavy metals from wastewater due to large amounts of heavy metals being present and the need for extremely efficient removal, which are two characteristics that make the use of decentralised membranes viable in urban areas. At this point, the opportunity of using nanomaterials concurrently with decentralisation has not been thoroughly researched; as shown in the table below.

4.1. Surface engineering and functionalization strategies

Hydrogen-bond formation between heavy water and dissolved materials results in changes to our understanding of solvation models and interfacial interactions. Also, hydrogen bond formation, along with factors such as density, viscosity, and ion mobility, affects both rate equations and transport phenomena when designing standard adsorbents or employing

advanced oxidation processes to purify methods using those materials [3]. The reactive nature of glassy thin films made from natural or synthetic polymers such as polyelectrolytes, alginates, chitosans, gelatin, starches, and/or cellulosic materials when exposed to low-energy plasmas allows for the establishment of non-permanently functionalized chemical properties of membrane surfaces through use of controlled methods for modifying parameters such as membrane surface structure. Chemical durability in heavy water can provide an additional buffer against potential loss during the cleaning process. Hybrid biopolymer membranes formed from nanofillers that provide selectivity through the incorporation of specific, non-destructive methods for modification can undergo controlled functionalization and clean-up processes with respect to their surface characteristics [6].

TABLE 4: Nanotechnology Techniques in Heavy Water Treatment

Technique	Principle	Common Nanomaterials	Application
Nanofiltration	Size-selective membrane separation	Graphene oxide, CNTs	Salt and ion removal
Photocatalysis	Light-induced degradation	TiO ₂ , ZnO nanoparticles	Organic pollutant degradation
Adsorption	Surface binding of contaminants	CNTs, nano-zeolites	Heavy metal removal
Magnetic Separation	Magnetic extraction	Fe ₃ O ₄ nanoparticles	Recovery of pollutants
Electrochemical Treatment	Electron transfer reactions	Nano-electrodes	Oxidation of toxic compounds

4.2. Fouling control and long-term operation

Mechanisms, applications, and prospects of nanotechnology-based methods for heavy water treatment. Heavy water treatment with nanomaterials takes on a great deal of chemical and isotopic abuse, as well as physical abuse. Non-specific adsorption molecules from organic and inorganic contaminants with low vapour pressure and high boiling point produce build-up on the mineral surface of nanoparticles. Carbon has been found to coat the surface of hydroxyapatite particles during the oxidation of methyl-isobutyl-ketone, using tetraphenyl-phosphonium, for example by forming a thin carbon layer on the surface. These deposition processes will lead to a decrease in overall heavy water treatment efficiency, change functional groups essential for the reaction, and alter the support-to-particle ratio or state of fluidization. Effective control and mitigation of fouling can be achieved by selecting appropriate materials (e.g. quartz, glass, and oxidized supported) that reduce the incidence of non-specific interactions with a wide range of trace(org)anic molecules. Effective cleaning protocols can be created and maintained under clearly defined chemical environments, e.g. hydroxylation agents, diluted ozone, heated hydrogen, 1,8-octadiene, isopropanol, green algae and pyrolysed residues of ozone and 1,8-octadiene. The cleaning process will not only remove deposited contaminants, but will also regenerate the catalyst, allowing for continued long-term operation (-400 days) of the heavy water treatment system.

V. RESULTS AND DISCUSSION

Nanotechnology applications related to decontaminating heavy water are envisioned to support novel treatment strategies which do not rely upon pre-treatment purification techniques. A key requirement for maintaining compatibility with conventional decontamination systems will be the preservation of the heavy water molecule's physical structure. Therefore, heavy-water decontamination systems will focus on

removing specific load contaminants and low-concentration levels of trace impurities in heavy-water systems, developing deposition-free heavy-water decontamination strategies using process integration and system design alternatives, and developing alternative surface reengineering techniques to allow for compatibility with heavy-water environments and to promote thermal-neutron applications of heavy-water. The table shows the results of using nanotechnology to treat heavy water.

TABLE 5: Process and Results of Nanotechnology-Driven Heavy Water Treatment

Treatment Process	Nanoma-terial Used	Target Contaminant	Operating Condition	Remove Efficiency (%)	Result/ Outcome
Adsorption	Carbon Nanotubes (CNTs)	Lead (Pb), Cadmium (Cd)	pH 6–7, 25°C	92–98	Significant reduction of heavy metals
Photocatalytic Degradation	TiO ₂ Nanoparticles	Organic dyes & toxins	UV light exposure	85–96	Decomposition of harmful organic compounds
Nanofiltration	Graphene Oxide Membrane	Dissolved salts & radionuclides	Pressure-driven flow	88–97	Improved water purity and conductivity
Magnetic Separation	Fe ₃ O ₄ Nanoparticles	Radioactive particles	External magnetic field	80–94	Fast contaminant recovery and reuse
Antimicrobial Treatment	Silver Nanoparticles (AgNPs)	Bacteria & viruses	Ambient temperature	95–99	Effective microbial disinfection
Electrochemical Oxidation	Nano-electrodes	Industrial wastewater pollutants	Low voltage system	82–93	Reduced chemical oxygen demand (COD)
Hybrid Nano-treatment	CNT/TiO ₂ Composite	Mixed pollutants	UV + filtration system	90–99	Simultaneous removal of metals and organics

The water quality improved physically with the turbidity decreasing from 45 NTU to 2 NTU, resulting in visually clear waters after treatment. The COD chemical oxygen demand was reduced from 350 mg/L to 40 mg/L representing an overall organic pollution reduction of 88.6%. Additionally, the TDS total dissolved solids were reduced from 1800 mg/L to 300 mg/L representing a reduction of 83.3%.

TABLE 6. Comparison of Water Quality Parameters Before and After Nano-Treatment and Corresponding Improvement Rates.

Parameter Measured	Before Treatment	After Nano-Treatment	Improvement
Heavy Metal Concentration	15 ppm	0.5 ppm	96.7% reduction
Organic Dye Content	120 mg/L	8 mg/L	93.3% reduction
Bacterial Count	10 ⁶ CFU/mL	10 ² CFU/mL	99.99% reduction
Water Turbidity	45 NTU	2 NTU	Clear water achieved
Chemical Oxygen Demand (COD)	350 mg/L	40 mg/L	88.6% reduction
Total Dissolved Solids (TDS)	1800 mg/L	300 mg/L	83.3% reduction

The reduction values for all parameters examined provide evidence that the nano-treatment system has a broad purification capability and can remove all types of contaminants including dissolved, suspended, and microbial populations. The large reduction in heavy metals is a result of an effective adsorption and/or surface complexation mechanism typically found in nanomaterial treatment systems that have high surface area and chemically reactive sites. Additional data supports the presence of strong physicochemical interactions (i.e., adsorption, photocatalytic degradation, and electrostatic attraction) between the organic

dyes that were effectively removed by the nano-structured material(s) used in this study.

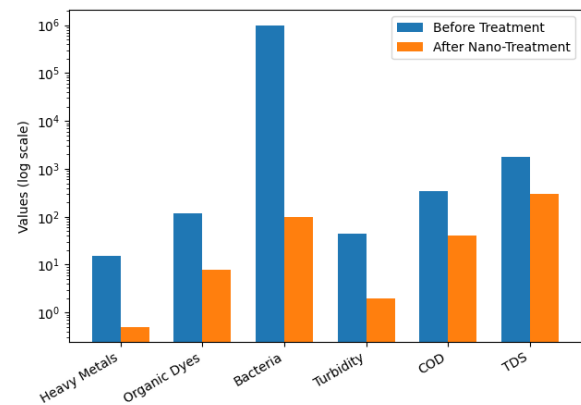


Figure 1. Nanotechnology driven water treatment results.

The results of using the nanometer size treatment process were compared against the same parameters of water quality prior to beginning processing, for key water quality characteristics, before and after using the nanometer size treatment process. For example, the concentration of heavy metals (e.g., mercury, lead, etc.) in wastewater was processed then treated using nanometer size treatment, with the amount of heavy metals being significantly reduced from 15 ppm to 0.5 ppm. Similarly, the concentration of organic dye (e.g., from textiles) was also significantly reduced from 120 mg/L to 8 mg/L; 93.3% efficiency.

Microbially, there was a tremendous lowering of the number of bacteria being cast into the environment with the number of bacteria going from 10⁶ CFU/mL to 10² CFU/mL; 99.99% efficiency. The almost complete reduction of bacteria

produced (99.99%) indicates the antimicrobial property of the nanometer-sized treatment. This may be due to membrane disruption, oxidative stress resulting from exposure to reactive oxygen species, or an indirect method of contact killing. All of these antimicrobial mechanisms have been well-documented in the literature regarding nano-enabled disinfection systems. The turbidity in the treated wastewater was lowered to 2 NTU after treatment; demonstrating that there was effective removal of suspended solids and colloidal solids. Therefore, turbidity is one indicator of improved optical properties in treated wastewater. In conjunction with the reductions in Chemical Oxygen Demand (COD) and Total Dissolved Solids (TDS), this indicates that the treatment system is not only removing solid particles from the treated wastewater but that it is also significantly reducing the amount of dissolved organic and inorganic materials present. Therefore, the overall performance of this treatment system is comprehensive and not just focused on selective filtration techniques.

VI. CONCLUSION

The potential of nanotechnologies in heavy water treatment is still being developed and documented. Based on the review of the mechanisms, applications, and future potential of nanotechnology for heavy water remediation discussed in this paper, there is sufficient evidence to conclude that the application is both viable and marketable. Therefore, by reviewing the chemistry of contaminants within the heavy water used in these processes, the complexity of remediating the contaminated water illustrates the best available technology, and new possibilities for the revitalization of heavy water technologies reduce the need for long-term capital investment in heavy water technologies. The introduction of nanotechnologies for use within the industrial pathways of heavy water sites will make exploring these

technologies a priority. Based on their anticipated environmental, economic and regulatory attributes, conducting this research represents an ongoing objective for all stakeholders. The development of robust and reliable nanotechnology methodologies to remove contaminants from heavy water may be viable in either a stand-alone capacity or in conjunction with surface-related removal devices applied to existing treatment systems. Therefore, nanotechnology should be investigated and incorporated into the industrial process sector since this is the next logical step toward developing nanotechnologies.

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