Engineering Perspectives in Filtration and Separation, Vol. 2, No. 4, December 2024
ISSN:3107-5290

Recent Patterns in the Usage of Nanomaterials and Nanofiltration Models for Pollutant Removal in Wastewater Treatment

Dr. Arvind Saxena[1] and Dr. Kavita Menon[2]*

[1]Senior Researcher, Department of Environmental Engineering, Indian Institute of Technology (IIT) Delhi, India.*

[2]Professor, Department of Environmental Engineering, Indian Institute of Technology (IIT) Delhi, India.

Abstract--- Water contamination presents substantial risks to ecosystems and human health. Addressing this issue necessitates efficiently treating home wastewater to transform trash into bio-fertilizers and gases. Disregarding liquid waste management incurs significant repercussions for public health and the ecosystem. This review examines advanced methods for the treatment of water and wastewater, with an emphasis on combating water-borne illnesses. It encompasses pollution avoidance and purifying techniques, such as hydrotherapy, membrane filtering, mechanical filtering, reversal osmosis, ion exchange, and copper-zinc cleansing. The article emphasizes extraction, field approaches, heavy metal elimination, and innovative technologies such as nanochips, graphite, Nanofiltration (NF), airborne water generations, and Wastewater Treatment Plants (WWTPs)-based remediation. The analysis highlights the importance of water purification for ecosystem preservation and human well-being, addressing pollution concerns and examining the incorporation of wastewater administration, coagulant methods, and Nanomaterial application in management strategies. Advanced biological processes, integrated with filtration, sterilization, and membranes, can enhance recovery rates by as much as 91%, exceeding the efficacy of standalone primary (<12%) or biological approaches (<52%). The future offers potential as modern purification methods improve water quality and accessibility, highlighting the necessity for responsible water preservation and administration to ensure sustainability.

Keywords--- Nanomaterials**,** Nanofiltration**,** Wastewater Treatment**,** Pollution.

Received: 17 - 09 - 2024; Revised: 21 - 10 - 2024; Accepted: 19 - 11 - 2024; Published: 27 - 12 - 2024

I. Introduction

Water is a prevalent natural resource essential for human survival and growth (Scanlon et al., 2023). The swift rise of urbanization and industrialization has led to an enormous increase in water use, making water scarcity critical for growing countries to address. A substantial volume of contaminated wastewater is discharged from multiple industries, including battery manufacture, mining, toxic substances, and electrolysis. Toxins in wastewater induce many detrimental effects on organisms and the surroundings (Karri et al., 2021). It proved a more efficient and cost-effective solution for treating factory wastewater. The types of contaminants in industrial wastewater depend on the production method. Wastewater from factories usually has a lot of harmful heavy metals, high salinity, a lot of organic substances, and more turbidity because of inorganic pollutants. Adsorption, flotation, chemical precipitation, membrane screening, flocculation, and coagulation are all parts of commercial wastewater treatment (WWT) (Wang et al., 2021). Sometimes, these cleaning methods aren't enough to eliminate specific contaminants, like harmful heavy metals, oil, and microbes.

There are many places where wastewater comes from, such as residential areas, businesses, industrial sites, and farming areas (Minhas et al., 2022). Significant differences in the chemical makeup of sewage are mainly determined by where it comes from. In addition to complex organic substances like feces, plant matter, food, proteins, organic substances, and nitrate, wastewater often has inorganic components like solutes, heavy metals, metallic ions, ammonium n, and gases. These can be found in surface water, groundwater, or water used by industries.

The World Health Organization (WHO) says that climate change and population growth make things worse for more than 2 billion people living in countries already struggling with water shortages. More than 2 billion people worldwide depend on unsafe water sources contaminated with feces, which poses a significant threat to the safety of drinking water. Public apprehension escalates over chemical hazards and developing pollutants, such as medicines, insecticides, and microplastics. Accessibility to safe water is essential for hygiene and avoiding diseases, particularly diarrhea, pneumonia, and tropical ailments (Mebrahtom et al., 2022).

This article thoroughly examines hydrotherapy, membrane cleansing, filtration, Reversal Osmosis (RO), ion exchange, and copper-zinc cleansing approaches to tackle this problem. It examines home techniques such as boiling, settling, filtering, purifying methods appropriate for field circumstances, and removing heavy metals.

Innovative methods such as nanochip-based and graphene-based cleansing, Nanofiltration (NF) water softening agents, airborne water creation, and plant water purifying precautions are emphasized (Arulnangai & Qureshi, 2023). The article examines the societal, wellness, and financial effects of water contamination, highlighting the advantages of pollution prevention and rehabilitation efforts. It incorporates traditional and modern WWT methods and examines the application of coagulating agents and Nanomaterials (NM) in sewage treatment (Manikandan et al., 2022).

II. Wastewater Treatment

WWT eliminates contaminants to render them safe for discharge or utilization. Methods differ according to the wastewater's nature and the treatment level required. The procedure entails initial treatment to eliminate substantial items and safeguard equipment. Solid substances are extracted using sedimentation and agitation. During the first treatment, particulates precipitate as sludge. Biological therapy degrades organic materials by the action of microorganisms. Prevalent techniques encompass activated wastewater, trickling filtration, and biological contacts. Supplementary measures eliminate contaminants by chemical reactions. Secondary treatment generates superior-quality water for reclamation.

Filtering and oxidation techniques are employed. Sludge necessitates additional processing, comprising thickening, dewatering, and stability (Cao et al., 2021). Sludge is utilized as fertilizer or thrown away in a landfill. The methods used are contingent upon the type of wastewater, regulatory frameworks, current facilities, and the resources at hand. Combinations can be utilized for efficacious treatment. Water treatment plants use various methods to eliminate pollutants and generate treated water for secure recycling or release. Water recovery is contingent upon the type of treatment procedure, the quality of incoming sewage, and the objectives for reuse.

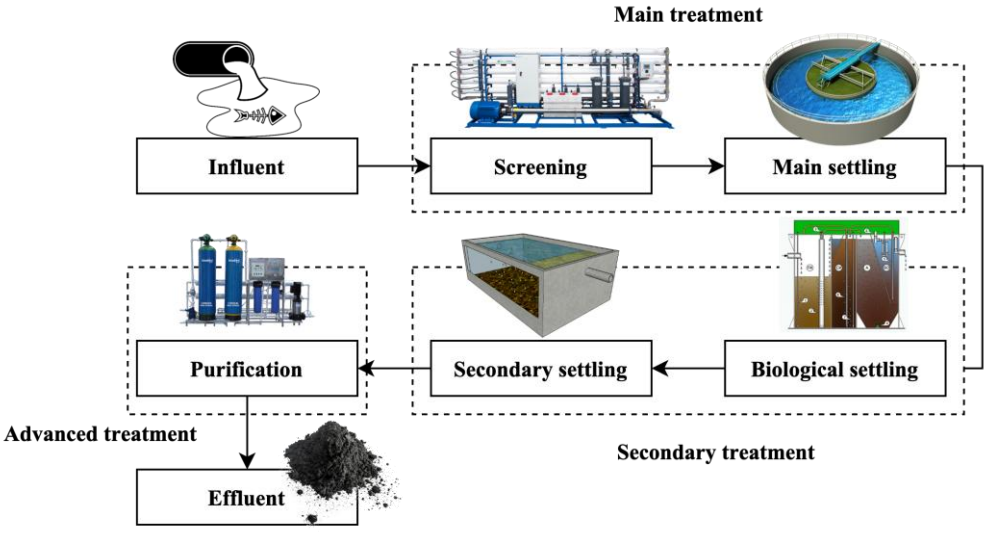


Figure 1: Wastewater Treatment

The following delineates the water collection rates for each phase: Primary treatment emphasizes physical procedures such as screening and centrifugation to eliminate bigger particles. Water recoveries are less than 12%; subsequent treatment employs biological methods to decompose organic materials further and destroy

nutrients. Water recovery can achieve 35-55%, representing a notable enhancement compared to primary processing; iii) Tertiary treatment improves water quality through filtration, disinfecting (e.g., chlorine or Ultra Violet (UV)), and membrane technology. Water recovery can achieve 70-90%, making it appropriate for reuse in irrigation or industrial operations; for uses necessitating more excellent water quality, extra methods like RO or advanced oxidation are utilized. Water recovery exceeds 85%, occasionally approaching 100%. Water recoveries in WWT facilities can vary from 75% to 90%, depending on treatment methodologies and particular reuse specifications. Every detoxification facility must balance recovering water with compliance with water quality requirements while addressing environmental rules and worries over water shortages.

Physical unit tasks depend on physical actions, while chemical unit activities utilize chemicals to eliminate or transform contaminants. Figure 1 illustrates the stages of WWT in sophisticated WWT Plants (WWTPs). Figure 2 demonstrates that biological unit activities eliminate contaminants via biological processes. The varying levels of treatment are attained by integrating unit operations and procedures. The initial treatment eliminates wastewater components that could lead to operational challenges, whereas the fundamental process reduces a portion of suspended solids and organic matter. The second process seeks to eliminate biodegradable organic matter and suspended materials via biological decomposition.

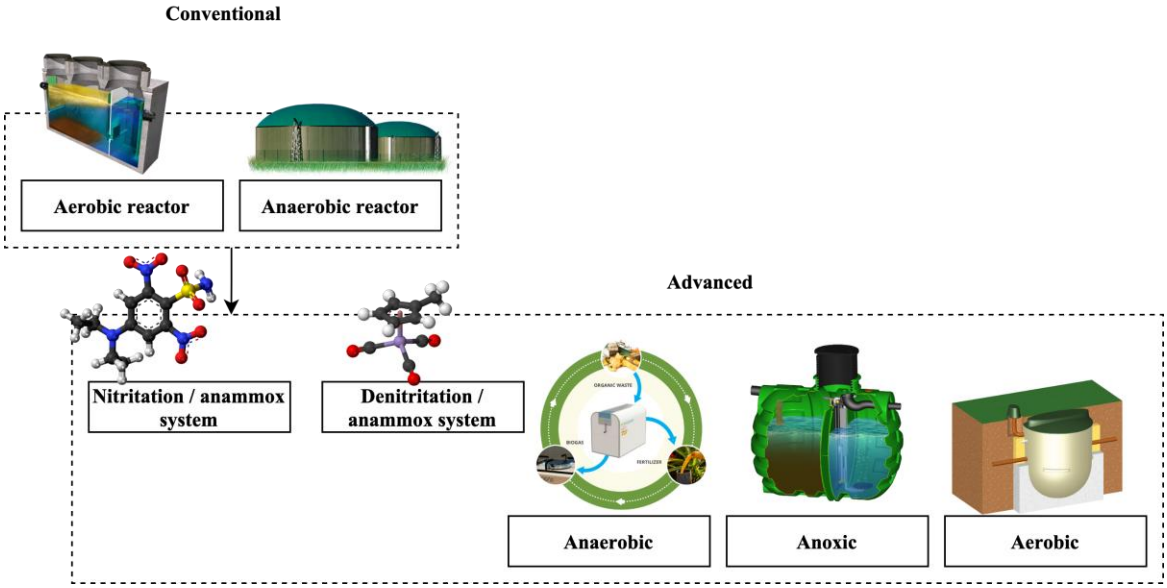


Figure 2: Biological Treatment Process

III. Usage of Nanomaterials

NF Filtration is essential for purifying water and WWT, as it separates particles from liquids using a filter or membranes. It serves a vital function in these procedures. Various filtering techniques encompass quicksand, multimedia, carbon filtering, and membrane filtering (microfiltration, ultrafiltration, NF, reversed osmosis). NF is an emerging membrane-separating technique utilized for purifying water and treatment of sewage. It depends on pressure, charge-induced repulsion, and an elevated penetrating speed. Filtering in WWT removes sludge and debris, enhancing quality and safeguarding equipment from harm. The selection is contingent upon treatment specifications and the required level of purity. NF eliminates suspended solids, sediments, particulates, and bacteria, enhancing the water quality. This is a crucial initial procedure before disinfecting or chemical disinfection, diminishing turbidity, and purifying water. NF is a widely favored energy-efficient alternative owing to its reduced pressure needs (7-30 atm) in contrast to RO techniques (25-120 atm). NF membranes possess attributes that lie between non-porous reverse osmosis membranes and porosity ultrafiltration filters. They predominantly depend on solution dispersion and membrane characteristics for transport. Some membranes in NF preferentially adsorb specific contaminants in the liquid. NF membranes possess a more effective separation process than RO filters. NF membranes, possessing pore widths of 1-6 nm, efficiently reject nearly all solutes. The exterior charge of the membrane facilitates the permeation of monovalent electrons in hard water while excluding multifaceted ions.

NF mainly rejects free-of-charge entities by size exclusion, while size restriction and electrostatic forces contribute to the rejection of ionic species. The application of NF in sewage treatment is novel and garners significant interest from many industries, including fabrics, pharmaceuticals, dairy, and petrochemical products. With its unique filtration mechanism and diverse membrane selections, NF efficiently eliminates inorganic and organic contaminants, including pathogenic microbes, from sewage. Artificial polymers dominate the composition of membranes for NF due to their manufacturability, exceptional flexibility, and low cost. In contrast, polymeric membranes exhibit inferior resistance to chemicals and a greater propensity for fouling, leading to a diminished lifespan.

Carbon NMs

Carbon Nanotubes (CNTs) are highly sought after for making membranes because they have unique properties. CNT pores of hollow nanotubes offer better contamination rejection and solvent entry. They work great for removing salt in water, cleaning water, and separating gases. CNT screens are easy to make using filtering, dip-coating, and thermal submitting, which lets you fine-tune the size and direction of the pores. The very long life of CNTs makes sure that the membranes don't change shape or break during high-pressure screening.

The nanoscale holes in CNT barriers can reject things, blocking unwanted substances while letting desired chemicals flow through. This trait makes it easier for separation and cleansing processes to work well. Because of the way their pores are sized, CNTs only let water pass through while blocking chemical and biological pollutants. Like clay barriers, barriers made of carbon nanotubes have the benefits of being both strong and flexible.

Zeolites

Zeolites are a type of aluminosilicate mineral that comes from volcanic ash or fluids that are high in silica. Their holes are different sizes, which lets chemicals enter and leave them selectively. Because zeolites are porous, they can be used as catalysts to separate gases, exchange ions, and clean water. Their large surface area helps chemicals work and keeps things in place. The properties of zeolites can be changed, which makes them useful for a wide range of tasks.

Because they are made of neutral crystals, zeolites work best for reverse osmosis and NF. NF membranes filled with zeolite offer resistance to heat and chemicals, successfully keeping organic contaminants in, improving thermal endurance, and reducing swelling. Scientists and engineers have devised ways to separate complex metals and molecules using zeolites' unique ability to absorb substances. Several fields use these methods to separate things, including petrochemical plants, gas production, and environmental cleanup.

Metallic Oxides

Metal oxides can be used in NF membranes without breaking the bank and show photocatalytic activity when exposed to light. Metal oxides like TiO2, ZnO, and Fe2O3 behave in this way. When exposed to radiation, they make pairs of electrons and holes that help redox processes happen on their surface. This process makes killing many types of water pollutants, including microorganisms, easier. Adding metal oxides to NF membranes improves their ability to do more than block physical objects. This reaction makes metal oxide-based membranes better at cleaning water by making it easier to eliminate larger particles, soluble organic substances, microbes, and pathogenic germs. Photocatalytic breakdown enhances water quality and filtration. TiOz nanoparticle mesh membrane removes Humic Acid (HA) and whole organic carbon from sewage. Metal oxides offer stability, resilience, and compliance with various membrane substrates. They can be readily integrated or applied to the membrane interface during production, enhancing performance without substantially altering the overall architecture.

Essential Variables for Pollutant Elimination

Given the expanding range of uses for Engineered Nanoparticles (ENPs) and the anticipated advancements in the area, ENPs are deliberately and inadvertently discharged from point and non-point sources into the soil and aquatic environments through WWTPs, waste management and atmospheric deposition (Figure 3).

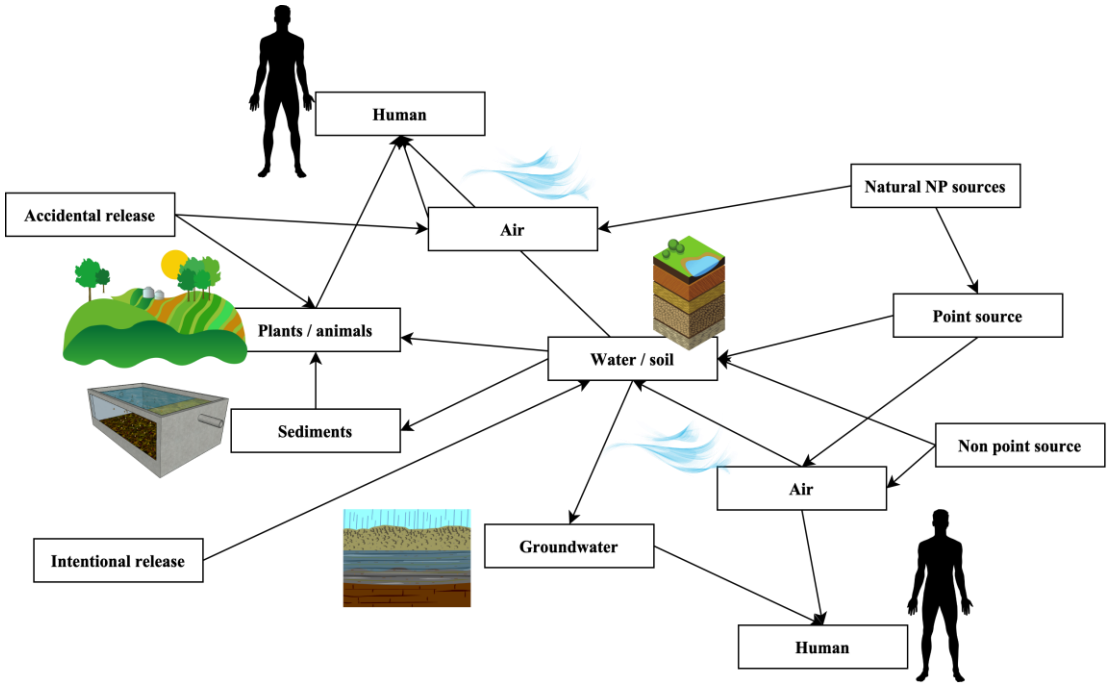


Figure 3: Essential Variables for Pollutant Elimination

Contaminants typically manifest in thick crude oil as either miscible or immiscible substances in water or as dispersed compounds such as metals, pigments, and insecticides. Collecting viscous oil involves more than just the procedure itself; it heavily depends on the denseness and porosity of the large composites for fluid density distribution via the small openings. Low-viscosity solvents penetrate the pores readily, whereas high-viscosity liquids are employed for slow diffusion. The structure of multifunctional materials can be heated by different methods utilizing the Joule operation, which reduces the thickness of oil, enabling a greater diffusion of oil into the cracks and facilitating expedited evacuation. The removal of water-dispersible contaminants relies on the electrostatic and chemical properties of the sorbent. These properties are enhanced by increasing the number of dynamic locations, such as area of coverage and charge, through chemical functioning.

Silicon graphene multifunction compounds can undergo surface functionalization to improve interactions with the analyte. The sub-atomic methodology represents a more astute method for enhancing the efficiency of silicon graphene compounds. The molecular holes enhance the detection capacities of dyes by concentrating on atoms. Molecular imprinting is advantageous for the development of silicon-graphene nanocomposites for the removal of toxic metals. Environmental factors have a crucial role in the adsorption of contaminants. The sorption mechanism fundamentally depends on the composite's physical condition, physicochemical characteristics, and the chemical makeup of pollutants in the water. The evaluation of attributes about material efficacy is crucial due to a shortage of characterization data and corresponding sorption capabilities, including specific surface areas. Notwithstanding these impediments, the research identified trends and successfully established linkages that enhanced the efficiency of the mixtures.

Reuse and Retention of NMs

Reusing nano-adsorbents and recovering components from aqueous solutions are significantly challenging and pose environmental issues; as chemicals are adsorbed, pre-treatment specimens must be prepared, followed by separation methods. Ballistic electrons emitted by the nanostructured materials' adsorbent substance and the nonporous carbonate under microwave irradiation eliminate the adsorbed chemical. The retention and recycling of NMs through membrane filtering are facilitated by innovative nanotechnology, which is essential for sustainable chemical utilization due to cost and health considerations. Ceramic membranes are advantageous over polymeric ones in photocatalytic processes due to their superior resistance to chemical antioxidants and UV radiation.

NMs can be manipulated on various membranes and resins, facilitating enhanced separation. Extensive research is required to advance cost-effective methods for immobilizing nanoparticles without compromising their effectiveness. The possibility of freedom depends on the separating procedure and the restraint approach

utilized. The breakdown of NMs that release metal ions must be meticulously controlled. Identifying NM release is a considerable, specialized challenge for risk assessment. It continues to be difficult, particularly in the context of the re-utilization of specific NMs to optimize cost processes. Two analytical needs exist for an NM intended for WWT. Future research under optimal, consistent circumstances is necessary to harness the efficiencies of diverse nanostructures.

Ecological Importance and Prospective Utilization

The efficacy of nanotechnology in manufacturing WWT is indisputable; their application presents numerous significant drawbacks, as they leach into the atmosphere during treatment procedures and pose enduring risks. Additional research and assessments are necessary to mitigate environmental toxicity. Titanium dioxide, a prevalent metal oxide nanoparticle, presents notable limitations and potentially hazardous effects on human health and the surroundings, thereby complicating the development of sustainable methods for eliminating atmospheric pollutants. Efforts for novel discoveries and research must be explored to surmount these challenges since numerous scientists and analyzers persistently work to conquer these barriers. A group of academics has just identified a more effective method to reduce the band gap for efficiently utilizing solar power.

The market demands the limitation of process costs related to the eco-friendly characteristics of the specified NMs. Sustainable development should be emphasized by utilizing material by-products from agricultural waste. A multitude of efforts in this domain is required for enhancement. The primary focus of the current research is that their application has not yet been realized in the study. A limited number of research articles on concise market analysis and economic factors are available. The primary market target for the future is to enhance the treatment method on a large scale, necessitating substantial financial and technological expenditures. Universities and research laboratories can play a significant role through a more formal approach to transferring technology and copyright safeguarding.

IV. Conclusion

Diverse categories of wastewater are produced by everyday activities, from companies, cafeterias, food processing facilities, residences, hospitals, and other prevalent sources. Slaughterhouses and fish markets generate substantial quantities of effluent. To promote societal advancement, it is essential to ensure adequate energy generation, accessible food resources, and efficient systems for handling waste. Proper sanitation and disposal are crucial; however, they are frequently deficient in densely populated coastal regions, slums, and communities for many reasons.

Unsustainable sanitation systems can pollute land, air, and water, endangering health. Industries frequently lead to water contamination by discharging sewage and waste, including human excrement, into water bodies and canals. Immediate measures are essential to avert more contamination of freshwater resources, especially the soil, and to guarantee their future viability. Addressing water contamination is a pressing issue requiring prompt action and efficient remedies. The research can diminish and eradicate water pollution by employing preventative measures and sophisticated purification techniques like aquatic therapy, membrane filtering, physical filtering, RO, ionic exchange water decreasing, and copper-zinc cleaning structures. To address water contamination, the research must utilize domestic procedures, such as boiling, settlement, and filtering, alongside specialized approaches designed for outdoor settings and the extraction of heavy metals.

Despite the obstacles posed by water pollution, tackling this issue yields substantial advantages, such as enhanced public health, bolstered farming and manufacturing, and safeguarding ecosystems. WWT is essential for reducing water contamination, and integrating traditional and modern systems, coupled with coagulating agents, can efficiently eliminate contaminants and lessen their effects on aquatic environments and organisms. Significant progress in NM-based technology has transformed the field of wastewater handling. Various uses of NMs, including photocatalysis, NF, and nano sorbents, have demonstrated their efficacy in tackling critical issues related to organic substances, toxic metals, and microbiological pollution in wastewater.

References

[1] Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., ... & Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, *4*(2), 87-101. https://doi.org/10.1038/s43017-022-00378-6

[2] Karri, R. R., Ravindran, G., & Dehghani, M. H. (2021). Wastewater—sources, toxicity, and their consequences to human health. In *Soft computing techniques in solid waste and wastewater management* (pp. 3-33). Elsevier. https://doi.org/10.1016/B978-0-12-824463-0.00001-X

[3] Wang, L. K., Wang, M. H. S., Shammas, N. K., & Hahn, H. H. (2021). Physicochemical treatment consisting of chemical coagulation, precipitation, sedimentation, and flotation. *Integrated natural resources research*, 265-397. https://doi.org/10.1007/978-3-030-61002-9_6

[4] Minhas, P. S., Saha, J. K., Dotaniya, M. L., Sarkar, A., & Saha, M. (2022). Wastewater irrigation in India: Current status, impacts and response options. *Science of the Total Environment*, *808*, 152001. https://doi.org/10.1016/j.scitotenv.2021.152001

[5] Mebrahtom, S., Worku, A., & Gage, D. J. (2022). The risk of water, sanitation and hygiene on diarrhea-related infant mortality in eastern Ethiopia: a population-based nested case-control. *BMC Public Health*, *22*(1), 343. https://doi.org/10.1186/s12889-022-12735-7

[6] Arulnangai, R., & Qureshi, A. K. (2023). Role of Nanomaterials in the Treatment of Polluted Cauvery River Water in Tiruchirappalli District (Tamil Nadu). In *Sustainable Nanomaterials for Biosystems Engineering* (pp. 297-318). Apple Academic Press.

[7] Manikandan, S., Subbaiya, R., Saravanan, M., Ponraj, M., Selvam, M., & Pugazhendhi, A. (2022). A critical review of advanced nanotechnology and hybrid membrane based water recycling, reuse, and wastewater treatment processes. *Chemosphere*, *289*, 132867. https://doi.org/10.1016/j.chemosphere.2021.132867

[8] Cao, B., Zhang, T., Zhang, W., & Wang, D. (2021). Enhanced technology based for sewage sludge deep dewatering: A critical review. *Water Research*, *189*, 116650. https://doi.org/10.1016/j.watres.2020.116650