ESP Journal of Engineering & Technology Advancements (ESP-JETA)
ISSN: 2583-2646

Special Issue: International Conference on Modern Engineering and Future Technologies (ICMEFT-26)

Original Article

Comparative Study on Fluoride Removal Using Natural Adsorbents, Nanomaterials and a Cost-Effective Hybrid Nano-Assisted Membrane System

Kartheeswari G[1], Saranya N[2]

[1]*UG Student, Department of Civil Engineering, P.S.R. Engineering College, Sivakasi, Tamilnadu, India – 626140.*

[2]*Assistant Professor, Department of Civil Engineering, P.S.R. Engineering College, Sivakasi, Tamilnadu, India – 626140.*

Abstract: *Groundwater contamination due to elevated levels of fluoride and Total Dissolved Solids (TDS) has emerged as a significant environmental and public health concern, particularly in semi-arid and rural regions. Prolonged consumption of fluoride-contaminated water leads to serious health issues such as dental fluorosis and skeletal fluorosis, thereby necessitating the development of efficient and affordable treatment methods. Conventional treatment techniques such as natural adsorbents and nanomaterial-based systems have been widely studied. Natural adsorbents are economical and environmentally sustainable; however, they suffer from relatively low adsorption capacity, especially under high TDS conditions. In contrast, nanomaterials exhibit superior removal efficiency due to their high surface area and enhanced physicochemical properties, but their practical application is restricted by high cost and operational complexity. In this study, a comparative analysis of natural adsorbents and nanomaterials is carried out based on existing literature, and a novel hybrid nano-assisted membrane system is proposed and experimentally investigated. The hybrid system integrates low-cost natural adsorbents with a nano membrane sheet to achieve improved fluoride removal efficiency while maintaining cost-effectiveness. Experimental results indicate that the hybrid system achieved a fluoride removal efficiency of 65.3%, reducing fluoride concentration from 3.69 mg/L to 1.28 mg/L. The findings demonstrate that the hybrid approach offers a balanced solution in terms of efficiency, cost, and sustainability, making it suitable for decentralized and rural water treatment applications.*

Keywords: *Comparative Study, Cost-Effective Treatment, Fluoride Removal, Hybrid Membrane, Nanotechnology, Natural Adsorbents.*

I. INTRODUCTION

Access to clean and safe drinking water is a fundamental requirement for human survival and socio-economic development. However, groundwater contamination has become a widespread issue due to both natural geological processes and anthropogenic activities. Among various contaminants, fluoride is one of the most critical pollutants affecting groundwater quality in many parts of the world, including India. Fluoride in drinking water, when present within permissible limits, is beneficial for dental health. However, excessive fluoride concentration beyond the recommended limits (1.5 mg/L as per WHO standards) leads to severe health problems such as dental fluorosis, skeletal fluorosis, and neurological disorders. In addition to fluoride, high Total Dissolved Solids (TDS) further degrade water quality, affecting its taste, hardness, and suitability for domestic use. Various methods have been developed for fluoride removal, including adsorption, ion exchange, reverse osmosis, and nanotechnology-based techniques. Among these, adsorption is considered one of the most efficient and economical methods. Natural adsorbents such as banana peel, neem bark, and other agricultural wastes have gained attention due to their low cost, availability, and eco-friendly nature. However, their efficiency is limited due to lower adsorption capacity and sensitivity to water chemistry conditions like high TDS.

On the other hand, nanotechnology has revolutionized water treatment processes by introducing materials with extremely high surface area, enhanced reactivity, and improved adsorption characteristics. Nanomaterials such as nano-metal oxides and carbon-based nanostructures provide high fluoride removal efficiency. Despite these advantages, their large-scale application is constrained by high production cost, regeneration issues, and technical complexity. To overcome these limitations, there is a growing need to develop hybrid systems that combine the advantages of both natural adsorbents and nanomaterials. Hybrid treatment systems aim to enhance removal efficiency while reducing operational cost and complexity. This study focuses on the comparative evaluation of natural adsorbents and nanomaterials based on literature and proposes a hybrid nano-assisted membrane system. The primary objective is to develop a cost-effective and efficient solution for fluoride removal that can be implemented in rural and resource-limited areas.

II. LITERATURE STUDY

Several studies have been carried out to investigate the effectiveness of different techniques for fluoride removal from groundwater. Natural adsorbents, nanomaterials, and membrane-based systems have been widely explored due to their varying efficiency and cost implications. Natural adsorbents derived from agricultural wastes such as banana peel and neem bark have been extensively studied due to their low cost, availability, and eco-friendly nature. Studies by Saravanan Ramasamy et al. (2024) and Ria Bhaumik and Naba Kumar Mondal (2016) reported that these materials exhibit moderate fluoride removal efficiency. However, their performance is significantly affected by high Total Dissolved Solids (TDS) and limited adsorption capacity.

Nanomaterial-based approaches have gained significant attention due to their superior adsorption properties. Junyong He et al. (2020) and Vijesh Prajapat and Trishikhi Raychoudhury (2025) highlighted that nanomaterials such as metal oxides and activated carbon-based nanostructures provide high fluoride removal efficiency, often exceeding 80%. Despite their effectiveness, these materials are associated with high cost, complex synthesis, and operational challenges. Membrane-based techniques, particularly nanofiltration membranes, have also been explored for fluoride removal. Fekri Abdulrageb Ahmed Ali et al. (2024) reported that polyamide nanofiltration membranes can effectively remove fluoride through selective separation mechanisms. However, these systems require higher initial investment and maintenance.

Additionally, studies such as those by Kalpana Singh et al. (2012) and C. B. Majumder (2021) emphasize that no single method is universally effective under all conditions, especially in groundwater with high TDS levels. From the literature, it is evident that natural adsorbents are economical but less efficient, while nanomaterials provide high efficiency at increased cost. This highlights the need for developing a hybrid system that combines the advantages of both methods.

III. MATERIALS AND METHODS

In the present study, experimental investigation was carried out only for the proposed hybrid system. The performance of natural adsorbents and nanomaterials was analyzed based on existing literature to enable a comparative evaluation.

A. Water Sample Collection

Groundwater samples were collected from borewell sources in Malli, Srivilliputhur, and stored in clean containers for laboratory analysis.

B. Physico-Chemical Analysis

The collected samples were analyzed for pH, TDS, hardness, chloride, sulphate, and fluoride using standard laboratory procedures.

C. Natural Adsorbent System (Literature-Based)

Natural adsorbents such as banana peel and neem bark have been reported in literature for fluoride removal due to their low cost and eco-friendly nature. However, their efficiency is limited in high TDS conditions.

D. Nanomaterial System (Literature-Based)

Nanomaterials provide high fluoride removal efficiency due to their enhanced surface properties and adsorption capacity. However, their use is limited by high cost and complexity.

E. Hybrid Membrane System (Proposed Model)

The proposed hybrid system was developed by integrating natural adsorbents with a nano membrane sheet. The system consists of:

- Natural adsorbent layer (banana peel + neem bark)
- Nano membrane sheet
- Supporting filter layer

Figure 1: Schematic diagram of hybrid nano-assisted membrane system

F. Study Approach

In this study, experimental investigation was carried out only for the proposed hybrid system. The performance of natural adsorbents and nanomaterials was evaluated based on existing literature for comparative analysis.

IV. RESULTS AND DISCUSSION

A. Initial Water Quality

- pH: 8.95
- TDS: 1960 ppm
- Fluoride: 3.69 mg/L

B. Post-Treatment Results (Hybrid System)

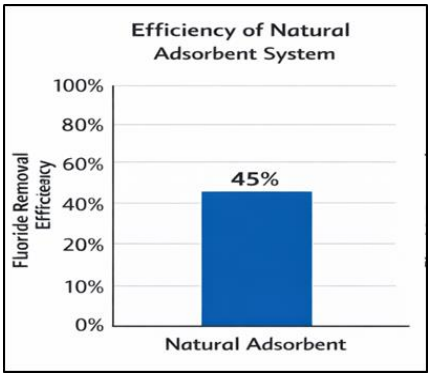
After treatment using the hybrid system:

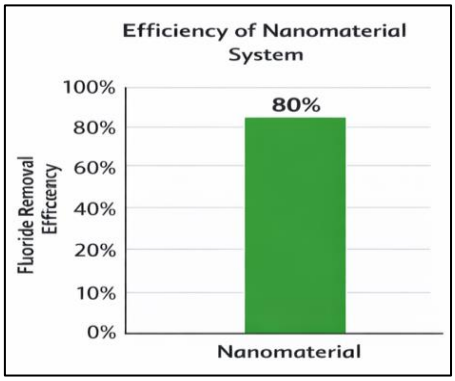
- Fluoride reduced from 3.69 mg/L to 1.28 mg/L
- Removal efficiency: 65.3%

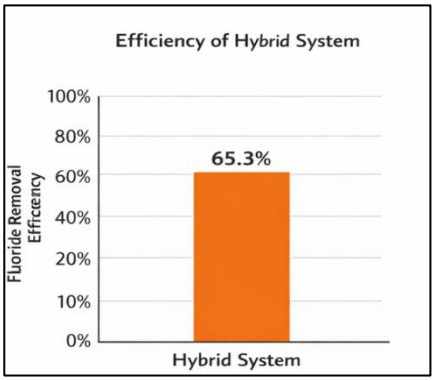
These results confirm that the hybrid system significantly improves water quality.

Table 1: Comparative Performance Analysis of Fluoride Removal Methods

Method	Cost	Efficiency	Limitation
Natural Adsorbents	Low	Low (~45%)	Less effective in high TDS
Nanomaterials	High	Very High (~80%)	Expensive and complex
Hybrid System	Low/Moderate	High (65.3%)	Requires optimization







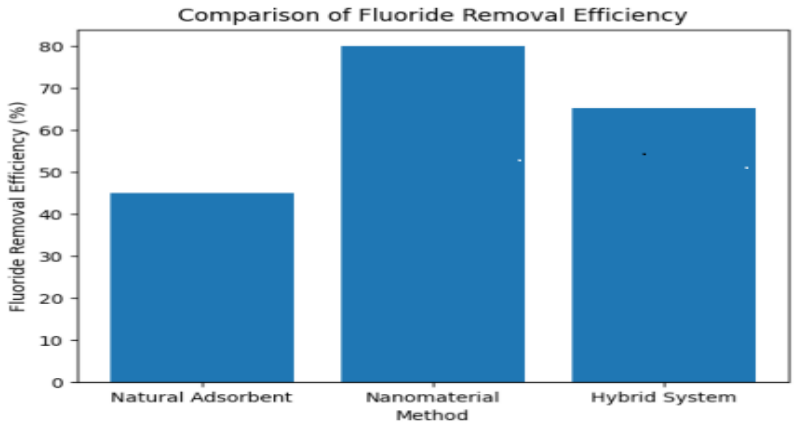


Figure 2: Comparison of fluoride removal efficiency among different methods

C. Discussion

The results obtained from the experimental investigation clearly demonstrate the effectiveness of the proposed hybrid nano-assisted membrane system in fluoride removal. The reduction of fluoride concentration from 3.69 mg/L to 1.28 mg/L indicates a significant improvement in water quality, bringing it closer to permissible limits.

The comparative analysis highlights the strengths and limitations of each method. Natural adsorbents, although economically viable and environmentally sustainable, exhibit limited adsorption capacity due to their relatively low surface area and lack of active binding sites. Their performance is further reduced in the presence of high TDS, which interferes with the adsorption process.

Nanomaterials, in contrast, provide superior performance due to their nanoscale size, high surface area-to-volume ratio, and enhanced adsorption properties. These materials offer rapid and efficient fluoride removal, often achieving efficiencies above 80%. However, their practical application is hindered by high cost, complex synthesis processes, and maintenance requirements.

The hybrid system developed in this study effectively bridges the gap between these two approaches. By incorporating a nano membrane sheet into a natural adsorbent-based system, the overall efficiency is significantly improved without drastically increasing the cost. The natural adsorbents act as a primary filtration and adsorption medium, while the nano membrane enhances removal efficiency by providing additional filtration and selective separation.

Another important advantage of the hybrid system is its adaptability for decentralized water treatment systems. It does not require highly sophisticated infrastructure or skilled operation, making it suitable for rural and semi-urban areas.

However, further optimization is required to improve the efficiency of the hybrid system and to evaluate its long-term performance, durability, and regeneration potential.

D. Innovation and Significance

The key innovation of this study is the partial integration of nanotechnology into a natural adsorbent system. This approach improves removal efficiency without significantly increasing cost, making it suitable for large-scale and rural applications.

V. CONCLUSION

The present study provides a comprehensive comparison of natural adsorbents, nanomaterials, and a proposed hybrid nano-assisted membrane system for fluoride removal from groundwater.

The findings indicate that natural adsorbents are cost-effective and environmentally friendly but exhibit lower efficiency, especially under high TDS conditions. Nanomaterials offer superior removal efficiency but are limited by high cost and operational complexity.

The proposed hybrid system successfully combines the advantages of both methods, achieving a fluoride removal efficiency of 65.3% while maintaining affordability. This demonstrates that partial integration of nanotechnology into conventional systems can significantly enhance performance without imposing a high economic burden.

The hybrid nano-assisted membrane system can be considered a promising solution for sustainable water treatment, particularly in rural and resource-constrained regions.

Future research should focus on improving system efficiency, exploring alternative nanomaterials, and evaluating large-scale implementation feasibility.

Thus, the proposed system provides a sustainable and scalable solution for safe drinking water in fluoride-affected regions.

VI. REFERENCES

[1] Saravanan Ramasamy et al. (2024), “Fluoride removal using natural bio-adsorbents”, International Journal of Environmental Research and Technology.
[2] Junyong He et al. (2020), “Review of fluoride removal by adsorption”, Journal of Water Process Engineering.
[3] Vijesh Prajapat and Trishikhi Raychoudhury (2025), “Fluoride removal using nanoparticles in groundwater”, Materials Today: Proceedings.
[4] Kalpana Singh et al. (2012), “Status and techniques of fluoride removal in water”, Environmental Science and Pollution Research.
[5] C. B. Majumder (2021), “Biological fluoride removal techniques: A review”, Journal of Environmental Management.
[6] Ria Bhaumik and Naba Kumar Mondal (2016), “Enhanced fluoride removal using modified banana peel adsorbent”, Journal of Environmental Chemical Engineering.
[7] Chen Yang et al. (2025), “Nanostructured MgO activated carbon for fluoride adsorption”, Materials Today: Proceedings.
[8] Fekri Abdulrageb Ahmed Ali et al. (2024), “Polyamide nanofiltration membrane for fluoride removal”, Desalination and Water Treatment Journal.
[9] Prathibha Chinnakoti et al. (2025), “Nanomaterials as nano-adsorbents for water purification”, Environmental Nanotechnology Journal.
[10] Abhay Kumar et al. (2024), “Effect of TDS on fluoride removal efficiency”, Journal of Water Supply and Treatment.