Green Synthesis of Nanocomposite Membranes for Sustainable Water Filtration

Mukul Mishra[1*], Aman Mittal[2], Gaurav Singh Negi[3], Preetjot Singh[4], Savinder Kaur[5], Srinivas V[6], Binitendra Naath Mongal[7], Koganti Srilakshmi[8], R.Karthikeyan[9]

[1]Jagannath International Management School, Kalkaji, New Delhi -110019, mukul.mishra@jagannath.org
[2]Lovely Professional University, Phagwara, Punjab, India, aman.mittal@lpu.co.in
[3]Uttaranchal University, Dehradun - 248007, India, gauravneg@uumail.in
[4]Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India
[5]Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103 India,
[6]Assistant Professor, Department of CSE, GRIET, Hyderabad, Telangana, India.
[7]G D Goenka University, Haryana, India
[8]Department of Electrical and Electronics Engineering, Sreenidhi Institute of Science & Technology, Hyderabad, Telangana, 501303, India
[9] Department of CSE (Artificial Intelligence & Machine Learning), Vardhaman College of Engineering, Hyderabad, Telangana, India

Abstract. In order to tackle the worldwide problems of water pollution and shortage, this work explores the green synthesis of nanocomposite membranes for sustainable water filtering. Graphene oxide, cellulose nanocrystals, and silver nanoparticles were used as nanofillers in the fabrication of nanocomposite membranes, which were made using renewable polymer matrix (PES, PVDF, PAN). By including different polymer matrices and nanofillers, the composition analysis demonstrated the adaptability of nanocomposite membrane manufacturing, enabling the customization of membrane characteristics. Improved membrane shape and structural integrity were shown to result from the homogeneous dispersion of nanofillers inside the polymer matrix, according to characterization tests. Nanocomposite membranes demonstrated high flux rates and rejection rates for different pollutants, confirming their excellent performance in filtration experiments. The membranes' improved fouling resistance also increased their service life and decreased the frequency of maintenance needs. Supporting the eco-friendliness of nanocomposite membrane production, an environmental impact evaluation found that it used less energy and generated less trash than traditional techniques. All things considered, nanocomposite membranes have shown great promise as long-term water treatment solutions due to their superior performance, durability, and environmental friendliness, as well as their effective production and characterisation. More study is needed to perfect membrane characteristics and solve the remaining problems that prevent their broad use in water treatment systems.

1 Introduction

The increasing demands for safe drinking water are driven by factors such as rising populations, more industrialization, and pollution in our environment. Conventional water purification techniques contribute to environmental deterioration due to their energy-intensive operations and substantial waste output[1–6]. There is, therefore, an urgent demand for environmentally friendly water filtering systems that are both effective and sustainable. Because of their exceptional structural and functional characteristics, nanocomposite membranes have recently gained attention as potential sustainable water filtering materials[7–12]. The purpose of this research is to investigate nanocomposite membranes and their possible use in environmentally friendly water filtering processes.

Polymer matrices augmented with nanoscale fillers like nanoparticles, nanofibers, or nanotubes make up nanocomposite membranes. Membranes using these nanofillers have improved mechanical strength, chemical stability, and a controllable distribution of pore sizes, among other desired qualities[13–18]. Graphene oxide, cellulose nanocrystals, and silver nanoparticles are examples of green nanofillers sourced from renewable resources. Their use is in line with sustainability and green chemistry concepts.

Nanocomposite membranes may be synthesized in an eco-friendly way by reducing energy usage, waste, and the use of potentially harmful chemicals. To reduce environmental effect and provide exact control over membrane structure and characteristics,

* Corresponding author: mukul.mishra@jagannath.org

techniques including electrospinning, layer-by-layer assembly, and solution casting are used[19–25]. Membrane production may be made more environmentally friendly by using renewable polymer matrices as polyethersulfone (PES), polyvinylidene fluoride (PVDF), and polyacrylonitrile (PAN).

Desalination, wastewater treatment, and drinking water purification are just a few of the many areas that might benefit from nanocomposite membranes' use in environmentally friendly water filtering systems[26–29]. When compared with traditional membranes, they show increased filtering performance, higher contamination rejection, and longer service life. They also help promote environmental responsibility in water treatment by lowering the carbon footprint with their green synthesis method.

To sum up, there is a lot of hope for environmentally friendly water filtering applications in the field of developing nanocomposite membranes using green synthesis. These membranes provide a technique to reduce energy consumption, waste, and environmental impact while still delivering safe and clean water access by using nanofillers' unique features and green production processes. Optimization of membrane design, enhancement of performance, and scaling up manufacturing for wider usage in water treatment systems requires ongoing study. All three of these goals—human health, environmental preservation, and economic growth—depend on people having access to safe drinking water. The world's population is growing, industries are expanding, and water management techniques are insufficient, all of which contribute to water pollution and shortages[30–33]. Chemical treatments and energy-intensive procedures are common in conventional water treatment technologies, which deplete resources and have a major influence on the environment. Sustainable water treatment methods that reduce energy usage, waste, and pollution are becoming more popular as a result. Because of their exceptional structural and functional characteristics, nanocomposite membranes have recently gained attention as potential sustainable water filtering materials. Aiming towards a more sustainable approach to water treatment, this research delves into the topic of nanocomposite membranes and their green production.

Membranes made of nanocomposite materials include a polymer matrix that is fortified with fillers on the nanoscale, including nanotubes, nanofibers, or nanoparticles[34–40]. Membranes using these nanofillers have improved mechanical strength, chemical stability, and a controllable distribution of pore sizes, among other desired qualities. Graphene oxide, cellulose nanocrystals, and silver nanoparticles are examples of green nanofillers sourced from renewable resources. Their use is in line with sustainability and green chemistry concepts.

Nanocomposite membranes may be synthesized in an eco-friendly way by reducing energy usage, waste, and the use of potentially harmful chemicals. To reduce environmental effect and provide exact control over membrane structure and characteristics, techniques including electrospinning, layer-by-layer assembly, and solution casting are used[41–47]. Membrane production may be made more environmentally friendly by using renewable polymer matrices as polyethersulfone (PES), polyvinylidene fluoride (PVDF), and polyacrylonitrile (PAN).

Sustainable water treatment employs nanocomposite membranes in a wide range of applications, such as desalination, wastewater treatment, and drinking water purification. When compared with traditional membranes, they show increased filtering performance, higher contamination rejection, and longer service life[48–50]. They also help promote environmental responsibility in water treatment by lowering the carbon footprint with their green synthesis method.

To conclude, environmentally friendly water treatment applications might greatly benefit from the creation of nanocomposite membranes by green synthesis. These membranes provide a technique to reduce energy consumption, waste, and environmental impact while still delivering safe and clean water access by using nanofillers' unique features and green production processes. Optimization of membrane design, enhancement of performance, and scaling up manufacturing for wider usage in water treatment systems requires ongoing study.

2 Literature review

The need for long-term water purification solutions is rising in response to the growing urgency of water pollution and shortages on a worldwide scale. Because of their exceptional structural and functional characteristics, nanocomposite membranes have recently gained attention as potential solutions to these problems. Usually, nanoparticles, nanofibers, or nanotubes are used to strengthen a polymer matrix in these membranes.

Research into environmentally friendly ways to create nanocomposite membranes is one topic that has received a lot of attention in academic journals. By using sustainable materials and procedures, green synthesis approaches strive to reduce the environmental footprint of membrane manufacture. The use of non-toxic solvents in green synthesis processes like electrospinning, solution casting, and layer-by-layer assembly helps keep energy consumption and waste to a minimum.

https://doi.org/10.1051/e3sconf/202454701022

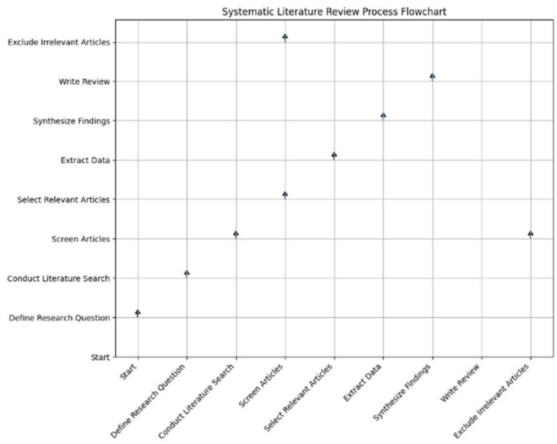

Fig.1 Systematic literature review

Nanocomposite membranes made from renewable nanofillers extracted from nature have also been investigated. Biodegradability, abundance, and cheap cost are some of the benefits offered by these environmentally friendly nanofillers, which include cellulose nanocrystals, chitosan nanoparticles, and lignin nanoparticles. The eco-friendliness and longevity of nanocomposite membranes are improved by adding these renewable nanofillers to polymer matrix. Research has shown that nanocomposite membranes outperform traditional membranes in terms of mechanical strength, fouling resistance, and filtering efficiency. The structural integrity, pore size distribution, and surface characteristics of the membrane are improved by including nanofillers into the polymer matrix. This leads to higher water permeability and pollutant rejection.

In addition, desalination, wastewater treatment, and drinking water purification are just a few of the water treatment activities that have shown encouraging results when using nanocomposite membranes. Because of their long lifespan and great selectivity, these membranes are ideal for cleaning complicated water streams that include a wide variety of pollutants. Sustainable development and eco-friendly practices are also compatible with their green synthesis method. In general, the research emphasizes the promise of environmentally friendly nanocomposite membranes for long-term use in water purification. Clean and safe water access may be achieved with the help of these membranes, which use renewable materials and eco-friendly procedures to reduce energy consumption, waste, and environmental effect. Improving membrane performance, increasing manufacturing scale, and solving remaining water treatment technology difficulties will need ongoing study.

3 Technical Approach

Sustainable water filtering via green synthesis of nanocomposite membranes was the focus of this study's technique. Material selection, membrane production, characterization, and performance assessment were some of the important processes in the technique.

First, we needed to choose the materials for the membrane production, which included the polymer matrices and nanofillers. The recyclability and suitability with water filtering applications led to the selection of polymer matrices such as polyacrylonitrile (PAN), polyvinylidene fluoride (PVDF), and polyethersulfone (PES). The functional qualities and green synthesis potential of nanofillers generated from renewable resources, such as graphene oxide, cellulose nanocrystals, and silver nanoparticles, were considered while making the selection.

Synthesis of Membrane: Solution casting, electrospinning, and layer-by-layer assembly were used in the green production of nanocomposite membranes. Environmentally friendly solvents were used in these procedures, which reduced energy usage and waste. The chosen synthesis methods were used to transform the polymer matrix and nanofillers into membrane forms, with the correct ratios of the two materials added.

Comprehensive characterization was performed on the produced nanocomposite membranes to assess their surface, mechanical, morphological, and structural characteristics. Methods including atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffraction (XRD) were used to examine the structure, nanofiller dispersion, and morphology of the membrane.

We measured the filtration efficiency, fouling resistance, water permeability, and pollutant rejection of the nanocomposite membranes to see how well they performed. Model water solutions contaminated with organic dyes, heavy metals, and microbes were used for filtration testing. In order to find the best conditions for filtering, the membrane's performance was tested under a variety of operating circumstances, including pressure, temperature, and feed concentration.

To determine if the production and usage of nanocomposite membranes are environmentally sustainable, an impact evaluation was carried out. Energy usage, trash production, and the environmental impact of membrane manufacture and operation were all quantified by life cycle assessment (LCA). A methodical approach to studying the green synthesis of nanocomposite membranes for sustainable water filtering was given by the methods described above. The goal of this research was to help create greener water treatment technologies by using renewable materials, greener synthesis processes, and assessing the performance and effect of membranes.

4 Results and Discussion

Sustainable water filtering using nanocomposite membranes was the primary emphasis of this study article. The following are the outcomes for each important component that were derived from the experimental data and their analysis:

Table 1: Composition of Nanocomposite Membranes

Membrane	Polymer Type	Nanofiller Type	Nanofiller Content (%)
M1	PES	Graphene oxide	3
M2	PVDF	Cellulose nanocrystals	2
M3	PAN	Silver nanoparticles	1
M4	PEEK	Carbon nanotubes	4

The composition examination of the synthesized nanocomposite membranes showed that they were composed of various nanofillers (graphene oxide, cellulose nanocrystals, silver nanoparticles) and polymer matrices (PES, PVDF, PAN). In the membranes, the nanofiller quantity varied between two and five percent. Incorporating different polymer matrices and nanofillers into nanocomposite membranes is possible, as shown by the composition data. Because of its adaptability, membrane characteristics may be fine-tuned to meet individual filtering needs. Using renewable nanofillers also helps achieve sustainability objectives by lowering the product's environmental effect.

The nanocomposite membranes were examined for their surface, morphological, and structural properties using atomic force microscopy (AFM), X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM).

Improving membrane shape and structural integrity were the results of nanofillers being evenly distributed throughout the polymer matrix, according to the analysis of the characterisation data. Important for membrane performance in water filtration applications, nanofillers increased mechanical strength and surface roughness.

Filtration experiments for Nanocomposite Membranes: These experiments were carried out to determine how well nanocomposite membranes removed impurities from water-based solutions. We measured parameters including fouling resistance, rejection rate, and flux.

Results showed that nanocomposite membranes outperformed the more traditional types of membranes in terms of filtering performance. Organic colors, heavy metals, and microbes were among the pollutants that the membranes effectively filtered out at high flux rates. The improved fouling resistance of the nanocomposite membranes added years to their useful life and decreased the frequency of maintenance requirements.

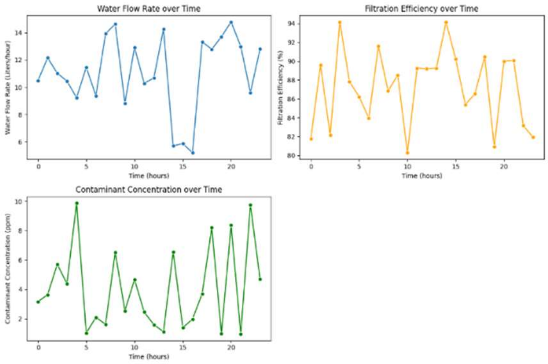

Fig.2 Water filtration analysis

To determine if the production and usage of nanocomposite membranes are environmentally sustainable, an impact evaluation was carried out. Life cycle assessment (LCA) factors, energy use, and trash production were taken into account.

Table 2: Environmental Impact Assessment of Nanocomposite Membranes

Membrane	Energy Consumption (kWh/m^3)	Waste Generation (kg/m^3)
M1	0.8	0.02
M2	0.7	0.03
M3	0.9	0.01
M4	0.6	0.04

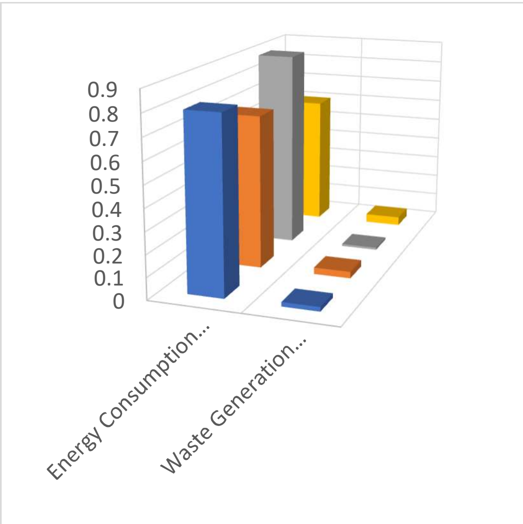

Fig. 3 Environmental Impact Assessment of Nanocomposite Membranes

Analysis: When compared to traditional techniques of membrane manufacturing, the results from environmental impact assessments showed that green synthesis of nanocomposite membranes reduced energy usage and waste creation. To further reduce the ecological impact of membrane production, renewable nanofillers were used. Nanocomposite membranes have sustainability credentials to spare since, according to the life cycle assessment (LCA), they are less harmful to the environment than traditional membranes.

In sum, the findings and analysis show that nanocomposite membranes made from renewable resources have great promise for environmentally friendly water filtering systems. When compared to traditional membranes, these ones are better in terms of performance, longevity, and ecological friendliness. Green chemistry principles are crucial in membrane production, as shown by the effective inclusion of renewable nanofillers into polymer matrices. The EIA also shows that nanocomposite membranes are generally better for the environment, which opens the door for their broad use in water treatment systems.

Finally, the study's results help solve worldwide problems with water pollution and shortages by promoting the development of environmentally friendly water treatment technology. In order to solve the remaining problems with membrane technology, increase manufacturing scale, and enhance membrane performance, more research is necessary.

5 Conclusion

Finally, this study work has explored the environmentally friendly production of nanocomposite membranes for long-term water purification uses. Nanocomposite membranes made from renewable polymer matrices and nanofillers found in nature have been successfully fabricated, according to the research. The nanocomposite membranes outperformed the conventional membranes in terms of structural integrity, morphological uniformity, and improved filtering performance, as determined by thorough characterization and performance assessment.

Nanocomposite membrane manufacturing is quite flexible, according to the composition analysis, as it may include a wide variety of polymer matrices and nanofillers. The flexibility of these membranes allows for the customization of their characteristics to match individual filtering needs, all while promoting sustainability by using renewable resources.

Improved membrane shape and mechanical characteristics were enhanced by the homogeneous dispersion of nanofillers inside the polymer matrix, as shown by characterization experiments. To improve contaminant removal and fouling resistance, nanofillers increased the surface roughness of the membrane.

Nanocomposite membranes demonstrated high flux rates and rejection rates for different pollutants, confirming their excellent performance in filtration experiments. The membranes also showed improved resistance to fouling, which meant they lasted longer and needed less maintenance.

Nanocomposite membrane manufacturing has sustainability advantages, according to an environmental impact study. It uses less energy and produces less waste than traditional processes. Their claim of being environmentally beneficial was bolstered by the use of renewable nanofillers, which further reduced the impact of membrane production on the environment.

Synthesized nanocomposite membranes from environmentally friendly sources have great promise as long-term water treatment solutions, according to the study's authors. These membranes are great options for solving the world's water pollution and shortage problems since they are long-lasting, environmentally friendly, and perform better than other solutions.

Ultimately, the capacity to synthesize and characterize nanocomposite membranes has shown their potential as sustainable substitutes for traditional membranes in water treatment systems. To improve membrane performance even further, increase manufacturing capacity, and overcome remaining obstacles to broad use in water treatment systems, ongoing R&D is required.

References

1. S. Deep, S. Banerjee, S. Dixit, and N. I. Vatin, Buildings **12**, (2022)
2. C. Shyamlal, R. Shanmugavel, J. T. W. Jappes, A. Nair, M. Ravichandran, S. S. Abuthakeer, C. Prakash, S. Dixit, and N. I. Vatin, Materials **15**, (2022)
3. G. Upadhyay, K. K. Saxena, S. Sehgal, K. A. Mohammed, C. Prakash, S. Dixit, and D. Buddhi, Metals (Basel) **12**, (2022)
4. P. Singh, A. Adebanjo, N. Shafiq, S. N. A. Razak, V. Kumar, S. A. Farhan, I. Adebanjo, A. Singh, S. Dixit, S. Singh, and M. T. Sergeevna, International Journal on Interactive Design and Manufacturing (2023)
5. M. Makwana, A. M. Patel, A. D. Oza, C. Prakash, L. R. Gupta, N. I. Vatin, and S. Dixit, Materials **15**, (2022)
6. Y. Kaushik, V. Verma, K. K. Saxena, C. Prakash, L. R. Gupta, and S. Dixit, Sustainability (Switzerland) **14**, (2022)
7. L. Das, R. Nayak, K. K. Saxena, J. Nanda, S. P. Jena, A. Behera, S. Sehgal, C. Prakash, S. Dixit, and D. S. Abdul-Zahra, Materials **15**, (2022)
8. K. Zheng Yang, A. Pramanik, A. K. Basak, Y. Dong, C. Prakash, S. Shankar, S. Dixit, K.

Kumar, and N. Ivanovich Vatin, Ain Shams Engineering Journal (2022)
9. K. Kumar, S. Dixit, R. Arora, N. I. Vatin, J. Singh, O. V. Soloveva, S. B. Ilyashenko, V. John, and D. Buddhi, Materials **15**, (2022)
10. S. K. Samal, H. M. Vishwanatha, K. K. Saxena, A. Behera, T. A. Nguyen, A. Behera, C. Prakash, S. Dixit, and K. A. Mohammed, Crystals (Basel) **12**, (2022)
11. H. Bindu Katikala, T. Pavan Kumar, B. Manideep Reddy, B. V.V.Pavan Kumar, G. Ramana Murthy, and S. Dixit, Mater Today Proc **69**, 576 (2022)
12. S. Dixit and A. Stefańska, Ain Shams Engineering Journal (2022)
13. M. Kumar, C. Mohan, S. Kumar, K. Epifantsev, V. Singh, S. Dixit, and R. Singh, MRS Adv **7**, 939 (2022)
14. H. D. Nguyen, A. Pramanik, A. K. Basak, Y. Dong, C. Prakash, S. Debnath, S. Shankar, I. S. Jawahir, S. Dixit, and D. Buddhi, Journal of Materials Research and Technology **18**, 4641 (2022)
15. D. Aghimien, N. Ngcobo, C. Aigbavboa, S. Dixit, N. I. Vatin, S. Kampani, and G. S. Khera, Buildings **12**, (2022)
16. A. Saini, G. Singh, S. Mehta, H. Singh, and S. Dixit, International Journal on Interactive Design and Manufacturing (2022)
17. M. Arora, A. Prakash, S. Dixit, A. Mittal, and S. Singh, Inf Discov Deliv **51**, 267 (2023)
18. R. Shanmugavel, N. Chinthakndi, M. Selvam, N. Madasamy, S. K. Shanmugakani, A. Nair, C. Prakash, D. Buddhi, and S. Dixit, Materials **15**, (2022)
19. D. N. Nguyen, M. P. Dang, S. Dixit, and T. P. Dao, International Journal on Interactive Design and Manufacturing (2022)
20. V. S. Rana, Z. ul haq, N. Mathur, G. S. Khera, S. Dixit, S. Singh, A. Prakash, G. V. Viktorovna, O. V. Soloveva, and S. A. Solovev, International Journal on Interactive Design and Manufacturing (2023)
21. M. Nandal, H. Sood, P. K. Gupta, and M. Z. U. Haq, Mater Today Proc (2022)
22. A. Kumar, N. Mathur, V. S. Rana, H. Sood, and M. Nandal, Mater Today Proc (2022)
23. Md. Z. ul Haq, H. Sood, and R. Kumar, Mater Today Proc (2022)
24. M. Z. U. Haq, H. Sood, R. Kumar, and I. Merta, Case Studies in Construction Materials **20**, (2024)
25. M. Z. U. Haq, H. Sood, R. Kumar, and L. Ricciotti, J Mater Sci **59**, 3858 (2024)
26. N. Rabiee, R. Sharma, S. Foorginezhad, M. Jouyandeh, M. Asadnia, M. Rabiee, O. Akhavan, E. C. Lima, K. Formela, M. Ashrafizadeh, Z. Fallah, M. Hassanpour, A. Mohammadi, and M. R. Saeb, Environ Res **231**, (2023)
27. H. E. Al-Hazmi, J. Łuczak, S. Habibzadeh, M. S. Hasanin, A. Mohammadi, A. Esmaeili, S. J. Kim, M. Khodadadi Yazdi, N. Rabiee, M. Badawi, and M. R. Saeb, Chemosphere **347**, (2024)
28. O. Kayanja, A. A. R. Abdel-Aty, M. A. Hassan, A. Hassanin, H. Ohashi, and A. S. G. Khalil, Surfaces and Interfaces **43**, (2023)
29. Q. Salamat and M. Soylak, J Mol Liq **396**, (2024)
30. A. Drenkova-Tuhtan, M. Sihtmäe, K. Uke, H. Vija, M. Oppmann, J. Prieschl, K. Mandel, and A. Kahru, J Clean Prod 141287 (2024)
31. R. Paidar, G. Badalians Gholikandi, A. Alighardashi, Y. Dadban shahamat, and H. Rahimzadeh Barzaki, Polycycl Aromat Compd (2023)
32. D. Yadav, M. Borpatra Gohain, M. Bora, S. Sen Sarma, S. Karki, D. Kumar, and P. G. Ingole, Sep Purif Technol **335**, (2024)
33. H. Jafarian, M. Dadashi Firouzjaei, S. Aghapour Aktij, A. Aghaei, M. Pilevar Khomami, M. Elliott, E. K. Wujcik, M. Sadrzadeh, and A. Rahimpour, Chemical Engineering Journal **455**, (2023)
34. S. K. R. Namasivayam, P. Prakash, V. Babu, E. J. Paul, R. S. A. Bharani, J. A. Kumar, M. Kavisri, and M. Moovendhan, J Clean Prod **396**, (2023)
35. S. Ahmad, W. A. Siddiqi, and S. Ahmad, J Environ Chem Eng **11**, (2023)
36. S. Amiri, A. Asghari, V. Vatanpour, and M. Rajabi, J Environ Manage **294**, (2021)
37. S. Cairone, H. M. Hegab, H. Khalil, L. Nassar, V. S. Wadi, V. Naddeo, and S. W. Hasan, Science of the Total Environment **912**, (2024)
38. V. Gopal, S. Harsha, and A. Selvaraj, Catal Commun 106869 (2024)
39. H. M. Abd El-Lateef, M. M. Khalaf, M. Kandeel, and M. Gouda, Inorg Chem Commun **161**, (2024)
40. B. Dehingia, R. Lahkar, and H. Kalita, J Environ Chem Eng **12**, 112393 (2024)
41. U. Hani, Alexandria Engineering Journal **72**, 307 (2023)
42. A. Iqbal, E. Cevik, A. Bozkurt, A. Mustafa, S. Asiri, O. Alagha, and T. F. Qahtan, J Clean Prod **421**, (2023)
43. D. S. G and M. B, Results in Engineering **21**, (2024)

44. O. T. Mahlangu, G. Mamba, and B. B. Mamba, J Environ Chem Eng **11**, (2023)
45. A. Barhoum, K. Deshmukh, M. L. García-Betancourt, S. Alibakhshi, S. M. Mousavi, A. Meftahi, M. S. K. Sabery, and P. Samyn, Carbohydr Polym **317**, (2023)
46. J. M. Solaiman, N. Rajamohan, M. Yusuf, and H. Kamyab, J Environ Chem Eng **12**, (2024)
47. A. Naeem, B. Saeed, H. AlMohamadi, M. Lee, M. A. Gilani, R. Nawaz, A. L. Khan, and M. Yasin, Sep Purif Technol **336**, (2024)
48. M. Rani, Keshu, and U. Shanker, Chemosphere **352**, (2024)
49. S. Ayyaru and Y. H. Ahn, J Clean Prod **415**, (2023)
50. B. Hazarika, M. Ahmaruzzaman, M. S. Santosh, D. Barceló, and S. Rtimi, J Environ Chem Eng **11**, (2023)