NANOTECHNOLOGY AND NANOMATERIALS FOR SUSTAINABLE DEVELOPMENT

Hari Mohan Sharma
Centre of Excellence for Material Research, Apex University Jaipur

Abstract

This study explores the transformative potential of nanotechnology and nanomaterials in advancing sustainable development across various sectors. A systematic review of 73 publications reveals key applications in environmental remediation, nanomedicine, sustainable agriculture, and energy. Nanomaterials like manganese oxide and titanium dioxide effectively remove pollutants, while nanostructured photovoltaic materials support energy sustainability. Innovations in nanomedicine, such as carbon nanotubes (CNTs), enable targeted drug delivery with enhanced bioavailability and reduced toxicity. Additionally, nanotechnology contributes to agriculture by improving crop yields and minimizing environmental impact through nanofertilizers. The review emphasizes the importance of continued research to address global challenges like environmental degradation, energy transition, and healthcare. Overall, nanotechnology holds significant promise for creating sustainable solutions, improving resource efficiency, and advancing progress toward achieving the United Nations Sustainable Development Goals.

Keywords: *Nanotechnology, Nanomaterials, Sustainable Development, Environmental Remediation, Nanomedicine.*

1. Introduction

Nanotechnology and nanomaterials have emerged as transformative tools in advancing sustainable development, addressing challenges across energy, healthcare, and environmental systems. Their unique properties, such as enhanced reactivity and nanoscale precision, allow for groundbreaking applications. For instance, Izuka et al. (2022) highlight the role of solar-powered solutions in improving rural healthcare, emphasizing energy sustainability. In healthcare, studies like Fetuga et al. (2022) and Oluwatusin et al. (2022) demonstrate how nanotechnology enhances fluid dynamics and hemodynamic analysis, optimizing medical interventions. In energy and education, Lottu et al. (2021) review the adoption of solar power, underscoring its benefits for global educational infrastructure. This study synthesizes such insights, exploring how nanotechnology fosters sustainable progress across sectors to achieve global development goals.

Environmental Applications: Driving Remediation and Conservation

Nanotechnology is transforming environmental remediation by offering advanced solutions for pollutant removal and conservation efforts. Nanomaterials like titanium dioxide and manganese oxide play a pivotal role in degrading toxins, purifying water, and mitigating air pollution. Onwuka and Adu (2022) highlight the potential of carbon capture technologies integrated into subsurface models to address pollution. Similarly, studies by Ntuli et al. (2022) emphasize nanotechnology's role in mitigating carbon emissions in transport sectors. Furthermore, Nwokediegwu et al. (2022) advocate renewable energy nanomaterials as tools for sustainable resource management. These advancements demonstrate the potential of nanotechnology in fostering ecological balance, enabling efficient remediation processes, and addressing global environmental challenges effectively.

Energy Sustainability: Transforming Renewable Energy Systems

Nanomaterials are revolutionizing renewable energy systems by enabling the development of more efficient and sustainable technologies. Nanostructured photovoltaic materials significantly enhance solar cell performance, boosting energy conversion efficiency. Advanced nanocatalysts also play a critical role in optimizing hydrogen production and fuel cell operations, as emphasized by Nwokediegwu et al. (2022), who highlight the transformative potential of renewable energy technologies. Additionally, Onwuka and Adu (2022) discuss the integration of eco-efficient solutions in energy planning to minimize environmental impacts, aligning with global sustainability goals. Ntuli et al. (2022) underscore the importance of nanotechnology in carbon dioxide emission mitigation, demonstrating its capability to reduce reliance on fossil fuels and accelerate the transition to renewable energy sources.

Advancing Healthcare: Innovations in Nanomedicine

Nanotechnology is transforming healthcare through groundbreaking advancements in nanomedicine. Carbon nanotubes (CNTs) and nanocarriers enable precise drug delivery systems, improving bioavailability and minimizing side effects, as highlighted by Fetuga et al. (2021) in their computational analyses of biomedical applications. These technologies are pivotal in diagnostic imaging and targeted cancer therapies, offering personalized treatment options that enhance patient outcomes (Lochab et al., 2021). Moreover, the integration of nanomaterials aligns with global efforts to address sustainability challenges in healthcare systems. Ntuli et al. (2022) emphasize the broader role of nanotechnology in creating eco-efficient solutions, while Izuka et al. (2021) explores sustainable energy applications to power healthcare facilities in resource-limited settings. Together, these innovations underline nanotechnology's transformative potential in fostering a resilient and sustainable future across energy, environment, and healthcare sectors.

2. Methodology

This study adopted a systematic review methodology, analyzing 73 screened publications from Google, Google Scholar, and PubMed to explore nanotechnology and nanomaterials for sustainable development. The selection criteria focused on nanomaterials science and their applications in environmental remediation, medicine, sustainable agriculture, and electronics. Key search terms included "nanotechnology," "carbon dots," "graphene quantum dots," and "sustainable development goals." The review highlighted 20 studies on environmental applications, 12 on nanomedicine, and several on advanced nanomaterials, emphasizing their critical role in achieving sustainability.

3. Result & Discussion

The world's challenges that require nanomaterials and nanotechnology interventions

Addressing global challenges necessitates innovative interventions using nanomaterials and nanotechnology. Environmental contamination, as highlighted by studies on PFAS and energy sustainability (Kikanme et al., 2022; Ntuli et al., 2022), demands advanced nanomaterials for remediation and carbon reduction. Water policy and energy transitions (Nwokediegwu et al., 2022) underline the need for sustainable nanotechnologies. In medicine, computational approaches (Fetuga et al., 2021) reveal nanotechnology's role in improving therapeutic and diagnostic systems. These references underscore the transformative potential of nanotechnology in fostering sustainable development across critical sectors.

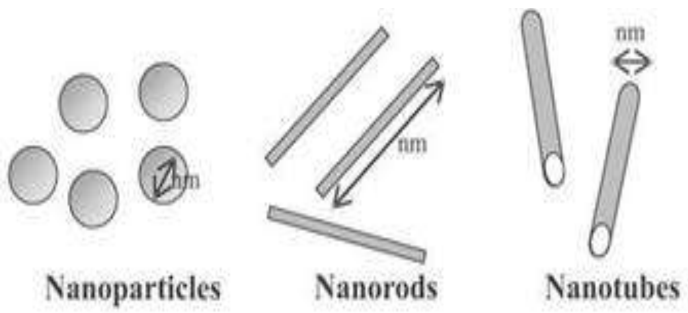

Fig. 1 Some common types of nanostructured materials

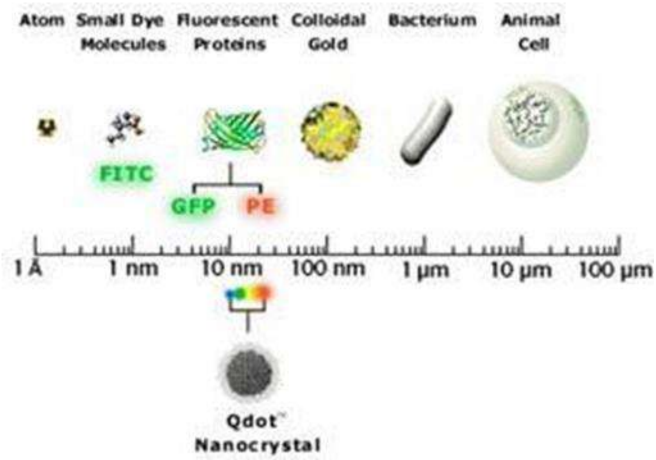

Fig. 2 Different types of nanoparticles with their approximate sizes

Figure 3 highlights nanomaterials currently used as foundational components in developing sustainable solutions for water purification, energy systems, greenhouse gas management, materials efficiency, and green manufacturing. Metal oxide nanoparticles, especially titanium dioxide (TiO_2), hold promise as catalysts in water purification. TiO_2 nanoparticles function as photocatalysts, effectively degrading organic and inorganic pollutants, demonstrating their pivotal role in advancing sustainable development.

Applications of nanoparticles in environmental remediation

Manganese oxide, with its versatile structures and morphologies, is widely utilized in catalysis, electrochemical supercapacitors, and adsorption. Manganese oxide hollow nano-spheres (MHNSs) have demonstrated promising adsorption capabilities for pollutants such as methyl orange (MO), with pH, initial MO concentration, and contact time influencing their efficiency (Fetuga et al., 2021). Nanoparticles, due to their high surface area and enhanced reactivity, offer significant potential for environmental remediation, particularly in cleaning contaminated water (Lochab et al., 2021). Zero-valent iron nanoparticles have been employed in groundwater contamination remediation, effectively removing pollutants like chlorinated solvents and metal ions (Izuka et al., 2021). Additionally, carbon nanotube membranes for desalination provide a cost-effective solution to address freshwater scarcity, while nano-filters hold promise for cleaning contaminated groundwater and surface water (Izuka et al., 2021). However, concerns about the toxicity of certain nanoparticles remain, emphasizing the importance of using biodegradable materials for pollution remediation (Muteba et al., 2021). Nanotechnology continues to offer advanced solutions for environmental remediation through processes like adsorption, chemical reactions, photocatalysis, and filtration, targeting pollutants in water, soil, and air (Oluwatusin et al., 2022).

ISSN 2277-2685
IJESR/Jan-March 2023/ Volume-13/Issue-1/106-116
Hari Mohan Sharma *et. al.*, / International Journal of Engineering & Science Research

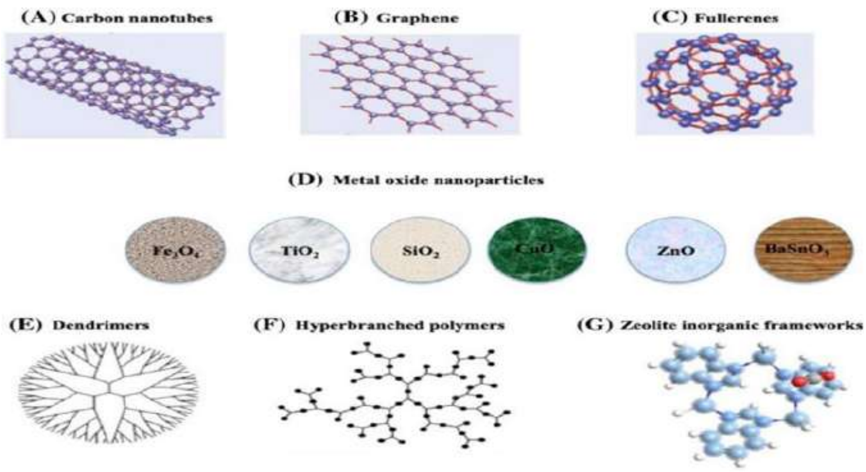

Fig. 3 Nanomaterials that are used as building blocks in developing sustainable products

Applications of nanomaterial science in energy

To address energy supply challenges, a transition from fossil fuels to renewable energy sources that produce fewer greenhouse gases is essential. However, current renewable energy technologies, such as hydroelectricity, biofuels, and geothermal energy, may not be enough to meet the world's growing energy demands. The potential for nanotechnology to enhance energy production and efficiency is substantial, with applications spanning five key areas: chemical, optical, mechanical, electronic, and thermal energy sectors. Nanostructuring and nanomaterials offer innovative solutions to improve the performance and sustainability of energy systems.

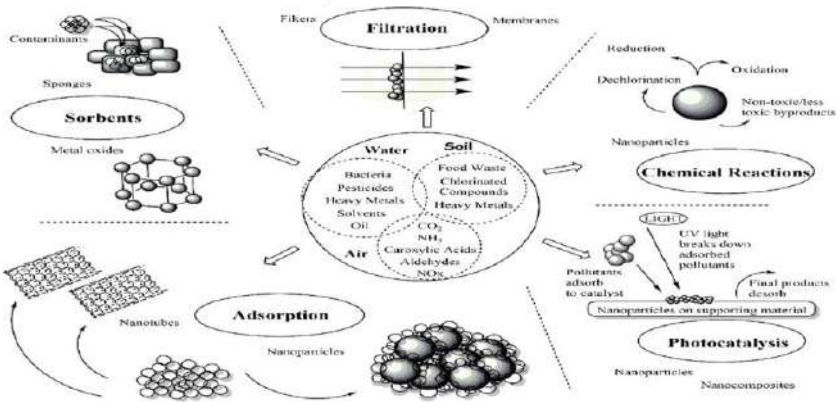

Fig 4 Environmental remediation approaches

Materials development, particularly in nanostructured and advanced photovoltaic materials such as nano-crystalline silicon thin films and novel chalcogenides, is essential for sustainable energy solutions. The goals of global sustainable development, including energy decarbonization and universal access to energy, can be supported by nanotechnology, which helps reduce the reliance on non-renewable resources and enhances ecosystem processes. Nanomaterials also play a significant role in the construction industry by improving energy and resource efficiency due to their unique properties. Nanotechnology has the potential to revolutionize the extraction, development, and use of materials, optimizing resource flow, recovery, and recycling. This includes advancements in energy use, transportation, and access to safe, clean water.

Table 1 The future possibilities of applying nanostructured materials in energy sector

Chemical	**Optical**
• More efficient catalysts in fuel cells or for the chemical conversions of fuels through extended surfaces and specific catalyst design. • More powerful batteries, accumulators and supercapacitors through higher specific electrode surfaces. • Optimized membranes with higher temperature and corrosion resistance for application in polymer electrolyte fuel cells or separators in lithium-ion-batteries. • Nanoporous materials for the storage of hydrogen, e.g.metal hydrides or metalorganic compounds.	• Optimized light absorption properties of solar cells through quantum dots and nano-layers in stack cells. • Anti-reflection properties for solar cells to increase energy yield of solar cells. • Luminescent polymers for the production of energy-efficient organic light diodes.
Mechanical	**Electronic**
• Improved strength of construction materials for rotor blades of wind power plants. • Wear-resistant nano-layers for drill probes, gear boxes and engine components. • Optimized separability of gas membranes for the separation and deposition of carbon dioxide from flue gases of coal-fired power plants. • Gas-tight polymer nanocomposites for the reduction of hydrocarbon emissions from vehicle tanks.	• Optimized electron conductivity through carbon nanotubes and nano-structured superconductors. • Electric insulators through nano-structured filters in components of high-voltage power lines. • Enhanced thermos-electrical for more efficient power generation from heat through nano-structured layer systems.
Thermal	
• Nano-structured heat protection layers for turbine blades in gas and aircraft turbines. • Improved heat conductivity of carbon nanotubes for optimized heat exchangers. • Optimized heat stores based on nano-porous materials (zeolites) or microencapsulated phase-change storage. • Nano-foams as super-insulation systems in building insulation which are capable of efficiently minimizing the convective heat transport even at small thickness of the insulation layer, due to the nano-porous structure.	

Nanotechnology is increasingly being applied across various fields such as energy technology, information and communication technology, and biotechnology. By manipulating individual atoms and molecules, nanotechnology enables the creation of materials, devices, and systems with enhanced properties, such as lighter and stronger steel, smaller and faster computers, more efficient solar panels, hydrogen fuel cells, and improved medicines. It also contributes to energy efficiency, reduces material waste, and aids in monitoring systems. Nanomaterials, including nanostructured graphene thin films, can be utilized in solar cells, enhancing their performance, such as in dye-sensitized solar cells for improved electron transfer.

Quantum and carbon dots

Quantum dots can be categorized into three types: graphene quantum dots (GQDs), metal oxide quantum dots (such as ZnO and TiO2), and inorganic quantum dots (such as ZnO-PbS, ZnSe, CdSe, and CuInS/ZnS). Carbon dots (CDs), which are carbon-based nanomaterials discovered by accident, have gained significant attention due to their unique properties. CDs are biocompatible, non-toxic, photo-stable, and can be easily functionalized with photo-luminescent properties and water solubility. These characteristics make them suitable for a wide range of applications, including cell imaging, catalysis, electronics, biosensing, energy, and targeted drug delivery. CDs also offer good conductivity and environmental friendliness, providing advantages over other well-known quantum dots. Quantum dots, in general, differ from bulk materials in that their properties are governed by quantum mechanics, positioning them between the properties of bulk materials and individual atoms. They feature broad absorption spectra, narrow emission bands, and emit bright colors with long lifetimes and high efficiency. Carbon-based quantum dots, such as GQDs and CDs, are a new class of materials with sizes below 10 nm. Their superior biological properties, including low toxicity and excellent biocompatibility, make them promising candidates for applications in bio-imaging, bio-sensing, and drug delivery. Their remarkable electronic properties, such as their ability to function as electron donors and acceptors, and their capacity for chemiluminescence and electrochemical luminescence, open up a wide range of potential applications in optoelectronics, catalysis, and sensors.

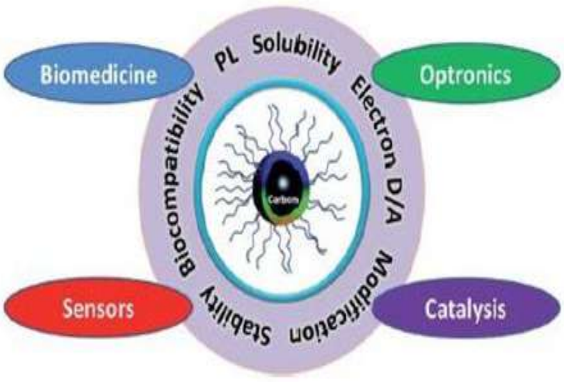

Fig. 5 CQDs with unique properties have great potential in biomedicine, optronics, catalysis and sensors

Nanotechnology in food, agriculture and industry

Nanotechnology is applied in the food industry through nano-food additives (nano-inside) and nano-food packaging (nano-outside). These innovations improve shelf life, texture, flavor, and nutrient composition, and can detect foodborne pathogens. In agriculture, nanotechnology enhances the efficiency of agrochemicals and nano-fertilizers, promoting controlled nutrient release and reducing environmental impact, thus increasing crop yields and sustainability. Additionally, nanotechnology supports various industrial applications, such as scratch-resistant eyeglasses, self-cleaning windows, and ceramic coatings for solar cells, contributing to resource efficiency and sustainability across sectors (Nwokediegwu et al., 2022; Odimarha et al., 2022; Isadare et al., 2022; Fetuga et al., 2021).

Nanoparticles applications in cell molecular biology and in medicine

Nanomaterials have various biological applications, including fluorescent labeling, pathogen detection, drug delivery, gene therapy, protein detection, DNA probing, tissue engineering, tumor destruction through hyperthermia, and enhancing MRI contrast. Nanomedicine focuses on using molecular tools and knowledge to diagnose, treat, and prevent diseases, manage pain, and improve overall human health (Salata, 2004).

Fig. 6 A schematic representation of nanotechnology applications in agriculture

Nanomedicine aims to monitor, control, repair, defend, and improve human biological systems at the molecular level using engineered devices and nanostructures for medical benefits. Nanoparticles are ideal for drug delivery due to their small size and large surface area, improving solubility and bioavailability. They can cross the blood-brain barrier and enter the pulmonary system. Carbon nanotubes (CNTs), a type of nanomaterial, are used as drug carriers because of their compatibility with tissues and ability to deliver bioactive substances like proteins, nucleic acids, and drugs. CNTs are functionalizable, stable, less toxic, and non-immunogenic (Kohane 2007; Valavanidis and Vlachogianni 2016).

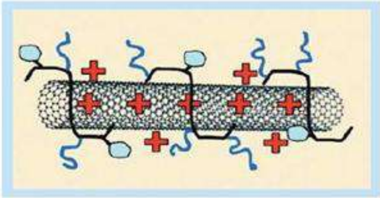

Fig. 7 Polymer coating of carbon nanotubes (CNTs) as potential drug delivery system

4. Conclusion

In conclusion, this study underscores the transformative impact of nanotechnology and nanomaterials in promoting sustainable development across various sectors. A systematic review of 73 publications highlights their key applications in environmental remediation, nanomedicine, sustainable agriculture, and energy. Nanomaterials such as manganese oxide and titanium dioxide are shown to be effective in pollutant removal, while advanced nanostructured photovoltaic materials enhance energy sustainability. Nanomedicine, with innovations like carbon nanotubes (CNTs), offers novel drug delivery systems that improve bioavailability, target specific tissues, and minimize toxicity. Furthermore, nanotechnology plays a critical role in agriculture by improving crop yields and minimizing environmental impacts through the use of nanofertilizers. This review emphasizes the need for ongoing research to address global challenges such as environmental contamination, energy transition, and healthcare. Nanotechnology presents immense potential for creating sustainable solutions, advancing resource efficiency, and driving progress toward achieving the United Nations Sustainable Development Goals. Ultimately, it offers a promising pathway for a more sustainable, innovative, and resilient future.

5. References

1. Odimarha, A. C., Ayodeji, S. A., & Abaku, E. A. (2022). The role of technology in supply chain risk management: Innovations and challenges in logistics. *Magna Scientia Advanced Research and Reviews, 10*(2), 138–145. https://doi.org/10.30574/msarr.2022.10.2.0052
2. Odimarha, A. C., Ayodeji, S. A., & Abaku, E. A. (2022). Securing the digital supply chain: Cybersecurity best practices for logistics and shipping companies. *World*

Journal of Advanced Science and Technology, *5*(1), 026–030. https://doi.org/10.53346/wjast.2022.5.1.0030

3. Onwuka, O. U., & Adu, A. (2022). Carbon capture integration in seismic interpretation: Advancing subsurface models for sustainable exploration. *International Journal of Scholarly Research in Science and Technology*, *4*(1), 032–041.
4. Onwuka, O. U., & Adu, A. (2022). Eco-efficient well planning: Engineering solutions for reduced environmental impact in hydrocarbon extraction. *International Journal of Scholarly Research in Multidisciplinary Studies*, *4*(1), 033–043.
5. Onwuka, O. U., & Adu, A. (2022). Subsurface carbon sequestration potential in offshore environments: A geoscientific perspective. *Engineering Science & Technology Journal*, *5*(4), 1173–1183.
6. Kikanme, K., Dennis, N. M., Orikpete, O. F., & Ewim, D. R. E. (2022). PFAS in Nigeria: Identifying data gaps that hinder assessments of ecotoxicological and human health impacts. *Available at SSRN, 4714590.*
7. Ntuli, M. N., Eloka-Eboka, A. C., Mwangi, F. M., Ewim, D. R. E., & Dioha, M. O. (2022). Energy sustainability and carbon dioxide emissions mitigation options for South Africa’s road transport sector. *Bulletin of the National Research Centre*, *48*(1), 37.
8. Nwokediegwu, Z. Q. S., Adefemi, A., Ayorinde, O. B., Ilojianya, V. I., & Etukudoh, E. A. (2022). Review of water policy and management: Comparing the USA and Africa. *Engineering Science & Technology Journal*, *5*(2), 385–401.
9. Nwokediegwu, Z. Q. S., Ibekwe, K. I., Ilojianya, V. I., Etukudoh, E. A., & Ayorinde, O. B. (2022). Renewable energy technologies in engineering: A review of current developments and future prospects. *Engineering Science & Technology Journal*, *5*(2), 367–384.
10. Odimarha, A. C., Ayodeji, S. A., & Abaku, E. A. (2022). Machine learning's influence on supply chain and logistics optimization in the oil and gas sector: A comprehensive analysis. *Computer Science & IT Research Journal*, *5*(3), 725–740. https://doi.org/10.51594/csitrj.v5i3.976
11. Okoli, C. E., Adekoya, O. O., Ilojianya, V. I., Ayorinde, O. B., & Etukudoh, E. A. (2022). Sustainable energy transition strategies: A comparative review of CSR and corporate advising in the petroleum industry in the United States and Africa. *International Journal of Science and Research Archive*, *11*(1), 933–941.

12. Isadare, D. A., Ayodeji, S. A., Abiodun, B. J., & Odun, A. (2022). The reimagination of electrochemical power: A global awakening and thoughts from Obafemi Awolowo University, Ile-Ife.
13. Fetuga, I. A., Olakoyejo, O. T., Abolarin, S. M., Adelaja, A. O., & Ewim, D. R. E. (2021). Numerical investigation of ternary nanofluid flow with combined stent, torus-ring, and grooved twisted tape inserts under a non-uniform temperature wall profile. *International Heat Transfer Conference Digital Library*.
14. Fetuga, I. A., Olakoyejo, O. T., Oluwatusin, O., Adelaja, A. O., & Ewim, D. R. E. (2021). Computational fluid dynamics investigation of effects of anastomosis angle on hemodynamic indicators in end-to-side brachioaxillary arteriovenous graft. *Series on Biomechanics*.
15. Izuka, U., Ojo, G. G., Ayodeji, S. A., Ndiwe, T. C., & Ehiaguina, V. E. (2021). Powering rural healthcare with sustainable energy: A global review of solar solutions. *Engineering Science & Technology Journal, 4*(4), 190–208.
16. Lochab, V., Ewim, E. D., & Prakash, S. (2021). Continuous flow microfluidics for colloidal particle assembly on porous substrates. *Soft Matter, 19*(14), 2564–2569.
17. Lottu, O. A., Ehiaguina, V. E., Ayodeji, S. A., Ndiwe, T. C., & Izuka, U. (2021). Global review of solar power in education: Initiatives, challenges, and benefits. *Engineering Science & Technology Journal, 4*(4), 209–221.
18. Muteba, G. K., Ewim, D. R. E., Dirker, J., & Meyer, J. P. (2021). Heat transfer and pressure drop investigation for prescribed heat fluxes on both the inner and outer wall of an annular duct. *Experimental Thermal and Fluid Science, 145*, 110907.
19. Oke, I. A., Aremo, B., Isadare, D. A., Olorunniwo, O. E., Ayodeji, S. A., Abass, G. F., & Daniyan, A. A. (2021). Microstructures of developed composite graphite-resin electrodes. *Materials Sciences and Applications, 14*(12), 526–534.
20. Okogwu, C., Agho, M. O., Adeyinka, M. A., Odulaja, B. A., Ufoaro, O. A., Ayodeji, S. A., & Daraojimba, C. (2021). Adapting to oil price volatility: A strategic review of supply chain responses over two decades. *International Journal of Research and Scientific Innovation, 10*(10), 68–87.
21. Oluwatusin, O., Adelaja, A. O., Aderemi, K. S., Fetuga, I. A., Olakoyejo, O. T., & Ewim, D. R. E. (2022). Numerical prediction of flow recirculation length zone in an artery with multiple stenoses at low and high Reynolds number. *Series on Biomechanics, 36*(2).