OPEN ACCESS
Engineering Science & Technology Journal
P-ISSN: 2708-8944, E-ISSN: 2708-8952
Volume 5, Issue 5, P.No. 1695-1710, May 2024
DOI: 10.51594/estj/v5i5.1137
Fair East Publishers
Journal Homepage: www.fepbl.com/index.php/estj

Nanotechnology's potential in advancing renewable energy solutions

Peter Simpa[1], Nko Okina Solomon[2], Olubunmi Adeolu Adenekan[3], & Scholar Chinenye Obasi[4]

[1]Faculty of Science and Engineering, University of Hull, UK
[2]Marshall University Huntington West Virginia.
US Department: Environmental Health and Safety, USA
[3]Independent Telecommunications Engineer and Data Analyst, UK
[4]University of South Wales, UK

*Corresponding Author: Peter Simpa
Corresponding Author Email: simpapeter@gmail.com

Article Received: 18-01-24 **Accepted:** 15-04-24 **Published:** 13-05-24

ABSTRACT

Nanotechnology has emerged as a promising frontier in the quest for sustainable energy solutions, offering transformative opportunities to address pressing challenges in renewable energy generation, storage, and conversion. This review explores the potential of nanotechnology in advancing renewable energy solutions, encompassing a wide range of applications spanning solar energy, wind energy, energy storage, and fuel cells. By leveraging the unique properties of nanomaterials, such as high surface area-to-volume ratio, tunable optical and electronic properties, and enhanced catalytic activity, researchers and engineers can develop innovative materials and devices with unprecedented performance and efficiency. Nanotechnology-enabled advancements in solar photovoltaics include the development of next-generation solar cells incorporating nanostructured materials, such as quantum dots, nanowires, and perovskite-based solar cells, to enhance light absorption, charge transport, and overall power conversion efficiency. In the realm of energy storage, nanomaterials hold promise for improving the performance and longevity of batteries, supercapacitors, and other energy storage devices through enhanced electrode materials, electrolytes, and nanostructured architectures. Furthermore, nanotechnology-driven innovations in wind energy, such as lightweight and durable nanocomposite materials for turbine blades, and advancements in fuel cell technologies, including catalyst nanoparticles for efficient hydrogen production and conversion, exemplify the diverse applications and transformative potential of nanotechnology in renewable energy. Through a comprehensive analysis of recent research and development efforts, this abstract underscores the critical role of nanotechnology in accelerating the transition to a sustainable and renewable energy future.

Keywords: Nanotechnology, Renewable Energy, Solar Energy, Wind Energy, Energy Storage, Nanomaterials.

INTRODUCTION

The transition towards sustainable and environmentally friendly energy sources has become imperative in the face of escalating global energy demand and the urgent need to combat climate change (Asif & Muneer, 2007). Renewable energy, harnessed from sources that are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat, offers a viable solution to these challenges (Ntuli et al., 2024; Uduafemhe et al., 2023). Unlike fossil fuels, renewable energy sources emit little to no greenhouse gases or pollutants, making them central to mitigating environmental degradation and fostering a sustainable future (Ewim, Abolarin, Scott, & Anyanwu, 2023; F. A. Rahman et al., 2017). The importance of renewable energy extends beyond environmental benefits; it also plays a crucial role in enhancing energy security, reducing dependence on imported fuels, and creating economic opportunities through job creation in renewable energy sectors (Dincer, 2000; Gielen et al., 2019; Hassan et al., 2024).

Despite the significant potential of renewable energy, technical and economic challenges hinder its widespread adoption and optimization. This is where nanotechnology comes into play (Ewim et al., 2023; Ehimare et al., 2023). Nanotechnology, the manipulation of matter on an atomic, molecular, and supramolecular scale, emerges as a transformative tool that can significantly enhance the efficiency and capabilities of renewable energy solutions. By developing nanomaterials and nanostructures, this technology can improve the performance of renewable energy devices, reduce manufacturing costs, and create novel energy conversion and storage systems (Ahmadi et al., 2019; Serrano, Rus, & Garcia-Martinez, 2009; Zhang, Uchaker, Candelaria, & Cao, 2013). For instance, in solar energy technologies, nanotechnology can increase the light absorption efficiency of photovoltaic cells, enabling the production of thinner, more flexible, and more efficient solar panels (Suku et al., 2023; Fawole et al., 2023). Similarly, nanotechnology can contribute to developing lighter and stronger materials for wind turbine blades, increasing their efficiency and durability (Patel & Mahajan, 2017).

This paper aims to explore the multifaceted role of nanotechnology in advancing renewable energy technologies and solutions. It aims to provide a comprehensive analysis of how nanotechnological innovations can address the current limitations of renewable energy systems, enhancing their efficiency, scalability, and cost-effectiveness (Orikpete and Ewim, 2023; Wiggins et al., 2023). By examining the impact of nanotechnology on various renewable energy sectors—including solar and wind energy, as well as energy storage—this paper seeks to highlight the potential of nanotechnology to revolutionize the energy landscape. Through a detailed exploration of the current advancements and prospects of nanotechnology in renewable energy, this paper aspires to contribute to the ongoing discourse on sustainable energy solutions and the critical role of technological innovation in achieving a sustainable energy future (Fetuga et al., 2023; Blose et al., 2023).

Nanotechnology in Solar Energy

The quest for cleaner, more sustainable energy solutions has led to significant interest and investment in solar energy, one of the most abundant and readily available renewable energy sources. However, solar panels' efficiency and economic viability have been longstanding challenges, limiting their widespread adoption (Onyiriuka et al., 2023; Abolarin et al., 2023). Nanotechnology, with its ability to manipulate materials at the molecular and atomic levels, has emerged as a key player in transforming solar energy technology, particularly in enhancing solar panel efficiency, innovating photovoltaic materials, and reducing manufacturing costs.

Enhancing Solar Panel Efficiency

One of the primary goals of solar energy technology is to maximize the conversion of sunlight into electricity, a challenge that nanotechnology is uniquely positioned to address. Nanomaterials can be engineered to absorb a broader spectrum of sunlight, including UV and infrared light, which traditional solar cells do not capture efficiently (Lochab et al., 2023; Muteba et al., 2023; Oluwatusin et al., 2022). Nanostructured solar cells, for example, use quantum dots or nanocrystals that can be tuned to absorb specific wavelengths of light more effectively than bulk materials. This tuning ability allows for the development of multi-junction solar cells, where different layers absorb different segments of the solar spectrum, significantly enhancing overall efficiency (Orikpete et al., 2020; Emeka-Okoli et al., 2024). Additionally, nanotechnology has enabled the creation of nano-coatings and plasmonic nanoparticles that can be applied to the surface of solar panels, reducing reflection and increasing the amount of light that enters the cell (Banin et al., 2020; Baxter et al., 2009).

Innovations in Photovoltaic Materials

The development of new nanomaterials is at the forefront of innovations in photovoltaic (PV) technologies, offering pathways to thinner, more flexible, and more efficient solar cells. Organic photovoltaic cells (OPVs), made from carbon-based polymers and molecules, are a promising area where nanotechnology plays a crucial role (Thompson et al., 2022). These materials can be engineered at the nanoscale to improve their electrical properties, leading to higher efficiency in converting sunlight into electricity. Moreover, the flexibility of these materials opens up new applications for solar cells, such as integrating them into clothing, portable electronics, and unconventional building materials, further expanding the utility and accessibility of solar energy (Kant & Singh, 2022; Raina, Sharma, Slathia, Bhagat, & Pathak, 2020; Sharma & Goyal, 2020).

Nanotechnology also contributes to the development of perovskite solar cells, which have shown remarkable progress in efficiency in a relatively short time frame. Nanoscale control over perovskite materials allows for fine-tuning their optical and electrical properties, enhancing their light-absorption capacity and charge-carrier mobility (Aturamu et al., 2024). This level of control not only boosts efficiency but also aids in overcoming stability issues that have hindered the commercialization of perovskite solar cells (Rajbongshi & Verma, 2019).

Reducing Manufacturing Costs

Beyond improving efficiency and enabling new materials, nanotechnology offers significant potential to reduce the costs associated with solar energy production (Akintuyi, 2024). Nanofabrication techniques, such as roll-to-roll processing and nanoprint lithography, can produce solar cells more quickly and with less material waste than traditional manufacturing processes. Similar to printing newspapers, these methods allow for the continuous production of flexible solar panels on lightweight and versatile substrates, drastically reducing material and production costs (Brunetti et al., 2019; Habas, Platt, van Hest, & Ginley, 2010).

Moreover, using nanomaterials can minimize the amount of expensive raw materials required, such as silver used in conductive pastes, by replacing them with cheaper nanoscale alternatives that perform the same function more efficiently (Ayorinde et al., 2024). This reduction in material usage, coupled with streamlined manufacturing processes, lowers the overall cost of solar energy, making it more competitive with traditional energy sources and more accessible to a broader range of consumers (Jagessar, 2021; Zareei et al., 2021).

In conclusion, nanotechnology holds the key to unlocking the full potential of solar energy, offering innovative solutions to enhance solar panels' efficiency, versatility, and cost-effectiveness (Nwokediegwu et al., 2024). By manipulating materials at the nanoscale, scientists and engineers are developing technologies that could revolutionize how we harness and utilize solar energy, paving the way for a cleaner, more sustainable energy future.

Nanotechnology in Wind Energy

As a pivotal component of the global renewable energy portfolio, wind energy offers substantial benefits for sustainable electricity generation. However, maximizing the efficiency and lifespan of wind turbines remains a challenge, necessitating innovative solutions to enhance their performance and durability (Okoli et al., 2024). Nanotechnology, with its capacity to engineer materials at the molecular level, has emerged as a transformative force in the wind energy sector, offering novel approaches to improving turbine blades, reducing maintenance through advanced coatings, and enhancing energy storage and transmission systems (Abdalla et al., 2020).

Improvements in Turbine Blades

The efficiency and performance of wind turbines are directly influenced by their blades' design and material composition. Nano-engineered materials are at the forefront of innovations to make turbine blades stronger, lighter, and more durable (Babcock). By incorporating nanocomposites—materials that combine nanoparticles with conventional composite materials—into the blade structure, engineers can significantly enhance the mechanical properties of the blades (Etukudoh et al., 2024; Usiagu et al., 2024). For instance, adding carbon nanotubes or graphene nanoparticles can increase the strength and fatigue resistance of the composite materials used in blades, allowing them to withstand harsh environmental conditions and operational stresses more effectively.

These nano-engineered composites also reduce the turbine blades' overall weight. Lighter blades require less energy to start rotating. They can operate more efficiently, especially in low wind conditions, thus increasing the energy conversion efficiency of wind turbines (Ayorinde et al., 2024; Daudu et al., 2024). Moreover, the enhanced durability of these materials reduces the likelihood of blade damage and failure, extending the lifespan of the turbines and reducing the need for costly repairs and replacements (Abdalla et al., 2020; F. A. Rahman et al., 2017; M. Rahman, Hussein, Shaikat, & Tasnim, 2020; Reddy, Suresh, MB, & Shivakumar, 2021).

Coatings and Maintenance

Wind turbines' operational efficiency and longevity are also hindered by wear and tear, which can be mitigated through nanotechnology applications in surface coatings (Ekemezie and Digitemie, 2024). Nano-coatings can be engineered to provide turbine blades with self-healing, anti-corrosion, and ice-phobic properties, significantly reducing maintenance requirements and operational downtime. For example, coatings with nano-sized particles can create a hydrophobic surface on the blades, preventing ice formation in cold climates and reducing the aerodynamic drag caused by rough blade surfaces. Similarly, nano-coatings can protect against UV radiation, saltwater corrosion, and mechanical abrasion, all contributing to the deterioration of blade materials over time (Dashtkar et al., 2019; Errichello, Sheng, Keller, & Greco, 2012).

Furthermore, applying these advanced coatings can enhance the aerodynamic performance of wind turbines. By maintaining a smoother blade surface, airflow over the blades is optimized, reducing drag and increasing the efficiency of energy generation (Digitemie and Ekemezie, 2024). This improvement in aerodynamics directly translates to higher power output and better overall performance of wind turbines.

Energy Storage and Transmission

The integration of wind energy into the power grid presents challenges related to the variability of wind and the need for efficient energy storage and transmission systems (Onwuk and Adu, 2024). Nanotechnology plays a crucial role in addressing these challenges, particularly in developing advanced materials for energy storage devices and enhancing electrical transmission components.

Nanostructured materials, such as nanoscale electrodes in batteries and supercapacitors, offer increased surface area and improved electrical conductivity, enhancing the efficiency and capacity of energy storage systems (Abaku et al., 2024). These improvements are vital for stabilizing the energy supply from wind turbines, allowing excess energy storage during peak wind periods and its release during low wind conditions (Liu, Sun, & You, 2014; Shukla & Prem Kumar, 2013).

Nanotechnology can improve the performance and efficiency of the materials used in transformers, conductors, and other components in electrical transmission (Abaku and Odimarha, 2024). For example, nano-engineered conductive materials can reduce energy loss during transmission, enabling more efficient delivery of wind-generated electricity over long distances. By reducing the resistivity and enhancing the thermal performance of these materials, nanotechnology contributes to minimizing energy losses and optimizing the overall efficiency of wind energy systems (Contreras, Rodriguez, & Taha-Tijerina, 2018; Elcock, 2007).

In conclusion, nanotechnology offers promising solutions to enhance the efficiency, durability, and integration of wind energy into the renewable energy mix (Eyo-Udo et al., 2024). Through innovations in turbine blade materials, surface coatings, and energy storage and transmission technologies, nanotechnology is paving the way for more reliable, efficient, and cost-effective wind energy systems, further solidifying wind power's role in the transition towards a sustainable energy future.

Nanotechnology in Energy Storage

The integration of renewable energy sources into the global energy mix is critical for achieving sustainability and reducing greenhouse gas emissions. However, the intermittent nature of renewable energy sources, such as solar and wind, necessitates advanced energy storage solutions to ensure a stable and reliable energy supply (Familoni et al., 2024). Nanotechnology, with its ability to manipulate materials at the atomic and molecular scale, offers groundbreaking advancements in energy storage technologies, including batteries, supercapacitors, and hydrogen storage systems (Pang, Cao, Zhu, & Zheng, 2020; Zäch, Hägglund, Chakarov, & Kasemo, 2006). These innovations are pivotal for enhancing energy storage devices' storage capacity, efficiency, and longevity, facilitating a smoother transition to renewable energy sources.

Advancements in Battery Technology

Nanotechnology has significantly impacted battery technology, particularly lithium-ion batteries, widely used in various applications from portable electronics to electric vehicles and renewable energy systems. Nanoscale materials can improve the performance of batteries in several key areas (Chen & Cheng, 2009; Mohan, Sharma, Kumar, & Gayathri, 2019; Pomerantseva, Bonaccorso, Feng, Cui, & Gogotsi, 2019; Shet, Priya, Sudhakar, & Tahir, 2021; Yang, Jung, Kim, & Park, 2012):

- Increased Storage Capacity: Nanomaterials, such as nanostructured electrodes, provide a larger surface area for the electrochemical reactions that power batteries (Odimarha et al., 2024a; Odimarha et al., 2024b; Odimarha et al., 2024c). This increase in surface area allows for greater energy storage capacity without significantly increasing the size of the battery.
- Enhanced Longevity: Batteries with nanoscale materials can endure more charge and discharge cycles before their performance degrades. This is due to the improved stability and reduced strain on materials at the nanoscale during the charging process, leading to a longer lifespan for the battery (Ekechi et al., 2024).
- Faster Charging Speeds: Nanotechnology facilitates quicker ion transport within the battery, enabling faster charging times (Akinsanya et al., 2024). Nanostructured electrodes allow ions to travel shorter distances and provide multiple pathways, significantly reducing the time required to charge the battery fully.

These improvements are essential for renewable energy systems, where efficient energy storage is crucial for balancing supply and demand, especially during periods when energy generation does not align with consumption patterns.

Supercapacitors

Supercapacitors, also known as ultracapacitors, benefit immensely from nanotechnology, offering a complementary solution to traditional battery storage (Popoola et al., 2024). Supercapacitors made with nanomaterials, such as carbon nanotubes and graphene, exhibit exceptionally high power density and the ability to release energy rapidly. This makes them ideal for applications requiring quick bursts of power, such as stabilizing the grid during sudden fluctuations in energy supply from renewable sources.

The advantage of supercapacitors lies in their longevity and fast charging capabilities, with the ability to undergo millions of charge-discharge cycles without significant degradation (Adama et al., 2024). While they currently have lower energy density than batteries, ongoing nanotechnology research aims to bridge this gap, making supercapacitors a more viable option for a wider range of energy storage applications.

Hydrogen Storage

Hydrogen storage is another area where nanotechnology holds promising potential, especially for hydrogen fuel cells, which are a clean and efficient energy source (Okogwu et al., 2023). The challenge with hydrogen storage is achieving high energy density in a compact, safe, and cost-effective manner. Nanomaterials can offer solutions by providing the following:

- High Surface Area for Adsorption: Nanomaterials with a high surface area, such as metal-organic frameworks (MOFs) and carbon nanotubes, can adsorb hydrogen at lower pressures and higher densities than traditional storage methods, improving the efficiency and safety of hydrogen storage.
- Enhanced Kinetics: Nanostructured materials can facilitate quicker hydrogen absorption and desorption, which is beneficial for the dynamic requirements of fuel cell vehicles and other applications where rapid response times are crucial.
- Compact Storage Solutions: The development of nanomaterials for hydrogen storage aims to reduce the volume required for storing hydrogen, making it more practical for a variety of applications, including transportation and portable power sources.

In conclusion, nanotechnology is revolutionizing energy storage technologies, offering significant advancements in the performance, efficiency, and application of batteries, supercapacitors, and hydrogen storage systems (Daniyan et al., 2024). These innovations are crucial for enhancing the viability and reliability of renewable energy sources, ultimately contributing to a sustainable energy future. By leveraging the unique properties of nanoscale materials, researchers and engineers are paving the way for more efficient, durable, and cost-effective energy storage solutions.

Challenges and Future Directions

The integration of nanotechnology into renewable energy solutions represents a significant leap forward in our pursuit of a sustainable energy future. However, this path is not without its challenges, encompassing technical and economic barriers and environmental and safety concerns. Addressing these issues is crucial for successfully adopting and implementing nanotechnology in renewable energy systems (Aremo et al., 2024). Moreover, identifying future research directions is essential for overcoming current limitations and unlocking the full potential of nanotechnology in this field.

Technical and Economic Challenges

The widespread adoption of nanotechnology in renewable energy faces several technical hurdles. One of the primary challenges is the scalability of nanomaterial production. While nanomaterials can significantly enhance the performance of renewable energy systems, producing these materials on a scale large enough to meet global energy demands remains a complex and costly process (Oke et al., 2023). Additionally, integrating nanomaterials into existing renewable energy technologies requires overcoming compatibility and stability issues, ensuring these innovations can withstand real-world environmental conditions over long periods.

Economically, the high cost of nanomaterials and the technologies required for their production and integration into renewable energy systems pose significant barriers (Izuka et al., 2023; Lottu et al., 2023). The initial investment for nanotechnology-enhanced renewable energy solutions is often higher than that for traditional energy systems, making it challenging to achieve competitive pricing. Furthermore, there is a need for economic assessments to fully understand the long-term cost savings and return on investment that nanotechnology can offer in the context of renewable energy.

Environmental and Safety Concerns

The environmental and health risks associated with nanomaterials' production, use, and disposal are significant concerns that must be addressed. Nanoparticles can have unique toxicological profiles, and their small size allows them to enter the human body and the environment more easily than larger particles (Popo-Olaniyan et al., 2022). The potential for bioaccumulation and the unknown long-term effects of nanomaterial exposure necessitate rigorous safety evaluations and the development of guidelines for the handling and disposal of these materials.

Moreover, the environmental impact of nanomaterial production, including resource consumption and emissions, requires careful consideration (Popo-Olaniyan et al., 2022). Developing sustainable and green synthesis methods for nanomaterials is essential to minimize the ecological footprint of nanotechnology in renewable energy applications.

Future Research Directions

Looking ahead, several key areas of research hold the promise of overcoming the current challenges and further leveraging nanotechnology for renewable energy solutions. Advancements in the green synthesis of nanomaterials are crucial for reducing both the environmental impact and the cost of nanomaterial production (Odimarha et al., 2024). Research into scalable and efficient production methods can address the technical and economic barriers to the widespread adoption of nanotechnology in renewable energy.

Innovations in nanomaterial design and functionality could lead to breakthroughs in energy conversion efficiency, storage capacity, and system durability. Exploring new nanomaterials and nanostructures with enhanced properties will be essential for advancing solar, wind, and energy storage technologies. Additionally, developing robust integration techniques for incorporating nanomaterials into existing renewable energy infrastructures is a critical area of research.

Furthermore, comprehensive lifecycle assessments and safety evaluations of nanomaterials used in renewable energy applications are needed to fully understand their environmental and health impacts. Developing standardized protocols for the safe production, handling, disposal, and recycling of nanomaterials is paramount to addressing safety and environmental concerns.

In conclusion, while nanotechnology offers transformative potential for renewable energy solutions, overcoming the current technical, economic, environmental, and safety challenges is essential for its successful implementation (Akinsanya et al., 2024). Future research directions will play a pivotal role in addressing these challenges, driving innovation, and unlocking new opportunities for leveraging nanotechnology in the pursuit of a sustainable energy future.

CONCLUSION

In conclusion, nanotechnology stands as a powerful ally in the quest for sustainable and efficient renewable energy solutions. Through advancements in materials science, nanotechnology offers unprecedented opportunities to enhance the performance, efficiency, and reliability of solar, wind, and energy storage technologies. Despite the challenges posed by scalability, cost, and environmental considerations, ongoing research and innovation are paving the way for overcoming these obstacles.

By addressing technical, economic, environmental, and safety concerns, the integration of nanotechnology into renewable energy systems can lead to significant advancements in global energy transition efforts. Future research directions promise to unlock even greater potential, driving innovation, and fostering the realization of a cleaner, more sustainable energy future for generations to come. As we continue to harness the transformative capabilities of nanotechnology, we move closer to realizing the vision of a world powered by renewable energy sources, where environmental stewardship and technological innovation go hand in hand.

References

Abaku, E.A., & Odimarha, A.C. (2024). Sustainable supply chain management in the medical industry: a theoretical and practical examination. *International Medical Science Research Journal*, *4*(3), 319–340. https://doi.org/10.51594/imsrj.v4i3.931

Abaku, E.A., Edunjobi, T.E., & Odimarha, A.C. (2024). Theoretical approaches to AI in supply chain optimization: Pathways to efficiency and resilience. *International Journal of Science and Technology Research Archive*, *6*(1), 092–107. https://doi.org/10.53771/ijstra.2024.6.1.0033.

Abolarin, S. M., Everts, M., Ewim, D. R. E., Adelaja, A. O., Olakoyejo, O. T., & Meyer, J. P. (2023). Study on the heat transfer and pressure drop power curves for entropy generation rate in the laminar, transitional, and turbulent flow regimes. *ASTFE Digital Library*, 1103-1112.

Abolarin, S. M., Everts, M., Ewim, D. R. E., Olakoyejo, O. T., Adelaja, A. O., & Meyer, J. P. (2023). Evaluation of the irreversibility distribution ratio and pumping power using heat transfer and pressure drop power curves of a smooth circular tube with laminar, transitional … International Heat Transfer Conference Digital Library.

Adama, H. E., Popoola, O. A., Okeke, C. D., & Akinoso, A. E. (2024). Economic theory and practical impacts of digital transformation in supply chain optimization. *International Journal of Advanced Economics*, *6*(4), 95-107.

Adama, H. E., Popoola, O. A., Okeke, C. D., & Akinoso, A. E. (2024). Theoretical frameworks supporting it and business strategy alignment for sustained competitive advantage. *International Journal of Management & Entrepreneurship Research*, *6*(4), 1273-1287.

Adefemi, A., Daudu, C. D., Okoli, C. E., Ayorinde, O. B., Adekoya, O. O., & Ibeh, C. V. (2024). Reviewing the development of floating LNG facilities and their global impact. *Engineering Science & Technology Journal*, *5*(2), 367-384.

Akinsanya, M. O., Ekechi, C. C., & Okeke, C. D. (2024). Data sovereignty and security in network engineering: A conceptual framework for compliance. *International Journal of Science and Research Archive*, *11*(2), 1832-1847.

Akinsanya, M. O., Ekechi, C. C., & Okeke, C. D. (2024). Security paradigms for iot in telecom networks: conceptual challenges and solution pathways. *Engineering Science & Technology Journal*, *5*(4), 1431-1451.

Akinsanya, M. O., Ekechi, C. C., & Okeke, C. D. (2024). The evolution of cyber resilience frameworks in network security: a conceptual analysis. *Computer Science & IT Research Journal*, *5*(4), 926-949.

Akinsanya, M. O., Ekechi, C. C., & Okeke, C. D. (2024). Theoretical underpinnings and practical implications of sd-wan technologies in telecommunications. *Computer Science & IT Research Journal*, *5*(4), 950-971.

Akinsanya, M. O., Ekechi, C. C., & Okeke, C. D. (2024). Virtual private networks (vpn): a conceptual review of security protocols and their application in modern networks. *Engineering Science & Technology Journal*, *5*(4), 1452-1472.

Akintuyi, O. B. (2024). Adaptive AI in Precision Agriculture: A Review: Investigating the use of self-learning algorithms in optimizing farm operations based on real-time data. *Research Journal of Multidisciplinary Studies, 7*(02), 016-030.

Akintuyi, O. B. (2024). AI in agriculture: A comparative review of developments in the USA and Africa. *Research Journal of Science and Engineering, 10*(02), 060–070.

Akintuyi, O. B. (2024). The role of artificial intelligence in U.S. agriculture: a review: assessing advancements, challenges, and the potential impact on food production and sustainability. *Open Access Research Journal of Engineering and Technology, 6*(02), 023–032.

Akintuyi, O. B. (2024). Vertical farming in urban environments: a review of architectural integration and food security. *Journal of Biology and Pharmacy, 10*(02), 114-126.

Aremo, B., Isadare, D. A., Akinduro, O. E., Bello, O. E., Adeoye, M. O., Ayodeji, S. A., ... & Oluwasegun, K. M. (2024). Production of glass ceramic from rice husk and periwinkle shells. *Discover Materials*, *4*(1), 8.

Aturamu, O. A., Thompson, O. A., & Banke, A. O. (2021). Forecasting the effect of climate variability on yam yield in rainforest and Guinea Savannah agro-ecological zone of Nigeria. *Journal of Global Agriculture and Ecology, 11*(4), 1-12.

Ayorinde, O. B., Daudu, C. D., Etukudoh, E. A., Adefemi, A., Adekoya, O. O., et al. (2024). Climate risk assessment in petroleum operations: A review of CSR practices for sustainable resilience in the United States and Africa. *Engineering Science & Technology Journal*, *5*(2), 385-401.

Ayorinde, O. B., Daudu, C. D., Okoli, C. E., Adefemi, A., Adekoya, O. O., & Ibeh, C. V. (2024). Reviewing the impact of LNG technology advancements on global energy markets. *Engineering Science & Technology Journal, 5*(2), 402-411.

Ayorinde, O. B., Etukudoh, E. A., Nwokediegwu, Z. Q. S., Ibekwe, K. I., & Umoh, A. A. (2024). Renewable energy projects in Africa: A review of climate finance strategies. *International Journal of Science and Research Archive*, *11*(1), 923-932.

Blose, S. C., Ewim, D. R. E., Eloka-Eboka, A. C., & Adelaja, A. O. (2023). Improved correlation for predicting heat transfer coefficients during condensation inside smooth horizontal tubes. *International Journal of Low-Carbon Technologies, 18*, 750-763.

Daniyan, A. A., Okonkwo, P. C., Ogundare, O. J., Oluwasegun, K. M., Umoru, L. E., Ayodeji, S., ... & Ige, O. O. (2024). Microstructural Characterization and Corrosion Behaviour of Heat Treated Standard Stainless Steels in Tar Sand. *Hybrid Advances*, 100195.

Daudu, C. D., Adefemi, A., Adekoya, O. O., Okoli, C. E., & Ayorinde, O. B. (2024). LNG and climate change: Evaluating its carbon footprint in comparison to other fossil fuels. *Engineering Science & Technology Journal*, *5*(2), 412-426.

Daudu, C. D., Okoli, C. E., Adefemi, A., Ayorinde, O. B., & Adekoya, O. O. (2024). Reviewing the economic viability of LNG projects in African nations. *World Journal of Advanced Research and Reviews, 21*(2), 109-118.

Digitemie, W. N., & Ekemezie, I. O., (2024). Assessing the role of climate finance in supporting developing nations: a comprehensive review. *Finance & Accounting Research Journal, 6,* 408-420.

Digitemie, W. N., & Ekemezie, I. O., (2024). Assessing the role of LNG in global carbon neutrality efforts: A project management review. GSC Advanced Research and Reviews, 2024, 18(03), 091–100.

Digitemie, W. N., & Ekemezie, I. O., (2024). Assessing the role of carbon pricing in global climate change mitigation strategies. *Magna Scientia Advanced Research and Reviews*, *2024*, *10*(02), 022–031.

Digitemie, W. N., & Ekemezie, I. O., (2024). Enhancing carbon capture and storage efficiency in the oil and gas sector: an integrated data science and geological approach. *Engineering Science & Technology Journal*, *5*, 924-934, March 2024.

Ehimare, E., Orikpete, O., & Ewim, D. R. E. (2023). The perennial logistical challenges during Nigerian elections: The unmanned aircraft system (UAS) solution.

Ekechi, C. C., Chukwurah, E. G., Oyeniyi, L. D., & Okeke, C. D. (2024). A review of small business growth strategies in African economies. *International Journal of Advanced Economics*, *6*(4), 76-94.

Ekechi, C. C., Chukwurah, E. G., Oyeniyi, L. D., & Okeke, C. D. (2024). AI-infused chatbots for customer support: a cross-country evaluation of user satisfaction in the USA and the UK. *International Journal of Management & Entrepreneurship Research*, *6*(4), 1259-1272.

Ekemezie, I. O., & Digitemie, W. N. (2024). Climate change mitigation strategies in the oil & gas sector: a review of practices and impact. *Engineering Science & Technology Journal*, *5*, 935-948, March 2024.

Ekemezie, I. O., & Digitemie, W. N. (2024). A review of sustainable project management practices in modern LNG industry initiatives. *World Journal of Advanced Engineering Technology and Sciences, 2024, 11*(02), 009–018.

Ekemezie, I. O., & Digitemie, W. N. (2024). Best practices in strategic project management across multinational corporations: a global perspective on success factors and challenges. *International Journal of Management & Entrepreneurship Research*, *6*, 795-805.

Ekemezie, I. O., & Digitemie, W. N. (2024). Carbon Capture and Utilization (CCU): A Review of Emerging Applications And Challenges. *Engineering Science & Technology Journal, 5,* 949-961, March 2024.

Ekemezie, I. O., & Digitemie, W. N. (2024). A comprehensive review of Building Energy Management Systems (BEMS) for Improved Efficiency. *World Journal of Advanced Research and Reviews, 2024, 21*(03), 829–841.

Emeka-Okoli, S., Nwankwo, T. C., Otonnah, C. A., & Nwankwo, E. (2024). Environmental stewardship and corporate social responsibility: A review of case studies from the oil and gas sector. *World Journal of Advanced Research and Reviews, 21*(3), 069-077.

Emeka-Okoli, S., Nwankwo, T. C., Otonnah, C. A., & Nwankwo, E. (2024). Communication strategies for effective CSR and stakeholder engagement in the oil & gas industry: A conceptual analysis. *World Journal of Advanced Research and Reviews, 21*(3), 091-099.

Emeka-Okoli, S., Nwankwo, T. C., Otonnah, C. A., & Nwankwo, E. (2024). The evolution of CSR reporting in the oil and gas industry and its future direction: A conceptual review. *World Journal of Advanced Research and Reviews, 21*(3), 100-108.

Emeka-Okoli, S., Nwankwo, T. C., Otonnah, C. A., & Nwankwo, E. (2024). Corporate governance and CSR for sustainability in Oil and Gas: Trends, challenges, and best practices: A review. *World Journal of Advanced Research and Reviews, 21*(3), 078-090.

Emeka-Okoli, S., Otonnah, C. A., Nwankwo, T. C., & Nwankwo, E. (2024). Internal and external communication in oil & gas for enhancing CSR implementation: A review. *World Journal of Advanced Research and Reviews, 21*(3), 109-118.

Etukudoh, E. A., Ilojianya, V. I., Ayorinde, O. B., Daudu, C. D., & Adefemi, A. (2024). Review of climate change impact on water availability in the USA and Africa. *International Journal of Science and Research Archive, 11*(1), 942-951.

Ewim, D. R. E., Nundlal, Y., Govender, K., Nzuke, N. L., Mbatha, M. V., & Gwexa, N. (2023). Knowledge, awareness, and perception of senior high school learners towards nuclear energy: A South African case study. *African Journal of Science, Technology, Innovation and Development, 15*(7).

Eyo-Udo, N.L., Odimarha, A.C., & Ejairu, E. (2024). Sustainable and ethical supply chain management: The role of HR in current practices and future directions. *Magna Scientia Advanced Research and Reviews, 10*(2), 181–196. https://doi.org/10.30574/msarr.2024.10.2.0058.

Eyo-Udo, N.L., Odimarha, A.C., & Kolade, O.O. (2024). Ethical supply chain management: balancing profit, social responsibility, and environmental stewardship. *International Journal of Management & Entrepreneurship Research, 6*(4), 1069–1077. https://doi.org/10.51594/ijmer.v6i4.985.

Familoni, B.T., Abaku, E.A., & Odimarha, A.C. (2024). Blockchain for enhancing small business security: A theoretical and practical exploration. *Open Access Research Journal of Multidisciplinary Studies, 7*(1), 149–162. https://doi.org/10.53022/oarjms.2024.7.1.0020.

Fawole, A. A., Orikpete, O. F., Ehiobu, N. N., & Ewim, D. R. E. (2023). Climate change implications of electronic waste: Strategies for sustainable management. *Bulletin of the National Research Centre, 47*(1), 147.

Fetuga, I. A., Olakoyejo, O. T., Abolarin, S. M., Adelaja, A. O., & Ewim, D. R. E. (2023). 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*.

Fetuga, I. A., Olakoyejo, O. T., Oluwatusin, O., Adelaja, A. O., & Ewim, D. R. E. (2023). Computational fluid dynamics investigation of effects of anastomosis angle on hemodynamic indicators in end-to-side brachioaxillary arteriovenous graft. *Series on Biomechanics.*

Isadare Dayo, A., Ayodeji Sodrudeen, A., Abiodun Bukunmi, J., & Odun, A. (2024). The re-imagination of electrochemical power: a global awak-ening and thoughts from Obafemi Awolowo University, Ile-Ife.

Izuka, U., Ojo, G. G., Ayodeji, S. A., Ndiwe, T. C., & Ehiaguina, V. E. (2023). Powering rural healthcare with sustainable energy: a global review of solar solutions. *Engineering Science & Technology Journal*, *4*(4), 190-208.

Kikanme, K., Dennis, N. M., Orikpete, O. F., & Ewim, D. R. E. (2024). PFAS in Nigeria: Identifying data gaps that hinder assessments of ecotoxicological and human health impacts. Available at SSRN 4714590.

Lochab, V., Ewim, E. D., & Prakash, S. (2023). Continuous flow microfluidics for colloidal particle assembly on porous substrates. *Soft Matter, 19*(14), 2564-2569.

Lottu, O. A., Ehiaguina, V. E., Ayodeji, S. A., Ndiwe, T. C., & Izuka, U. (2023). Global review of solar power in education: initiatives, challenges, and benefits. *Engineering Science & Technology Journal*, *4*(4), 209-221.

Muteba, G. K., Ewim, D. R. E., Dirker, J., & Meyer, J. P. (2023). 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.

Ntuli, M. N., Eloka-Eboka, A. C., Mwangi, F. M., Ewim, D. R. E., & Dioha, M. O. (2024). Energy sustainability and carbon dioxide emissions mitigation options for South Africa’s road transport sector. *Bulletin of the National Research Centre, 48*(1), 37.

Nwokediegwu, Z. Q. S., Adefemi, A., Ayorinde, O. B., Ilojianya, V. I., & Etukudoh, E. A. (2024). Review of water policy and management: Comparing the USA and Africa. *Engineering Science & Technology Journal, 5*(2), 385-401.

Nwokediegwu, Z. Q. S., Ibekwe, K. I., Ilojianya, V. I., Etukudoh, E. A., & Ayorinde, O. B. (2024). Renewable energy technologies in engineering: A review of current developments and future prospects. *Engineering Science & Technology Journal, 5*(2), 367-384.

Odimarha, A. C., Ayodeji, S. A., & Abaku, E. A. (2024). 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.

Odimarha, A. C., Ayodeji, S. A., & Abaku, E. A. (2024). The role of technology in supply chain risk management: Innovations and challenges in logistics. *Magna Scientia Advanced Research and Reviews*, *10*(2), 138-145.

Odimarha, A.C., Ayodeji, S.A., & Abaku, E.A. (2024a). 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.

Odimarha, A.C., Ayodeji, S.A., & Abaku, E.A. (2024b). 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.2024.5.1.0030.

Odimarha, A.C., Ayodeji, S.A., & Abaku, E.A. (2024c). 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.2024.10.2.0052.

Oke, I. A., Aremo, B., Isadare, D. A., Olorunniwo, O. E., Ayodeji, S. A., Abass, G. F., & Daniyan, A. A. (2023). Microstructures of developed composite graphite-resin electrodes. *Materials Sciences and Applications*, *14*(12), 526-534.

Okogwu, C., Agho, M. O., Adeyinka, M. A., Odulaja, B. A., Ufoaro, O. A., Ayodeji, S. A., & Daraojimba, C. (2023). 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.

Okoli, C. E., Adekoya, O. O., Ilojianya, V. I., Ayorinde, O. B., & Etukudoh, E. A. (2024). 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.

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).

Onwuka, O. U., & Adu, A. (2024). Carbon capture integration in seismic interpretation: Advancing subsurface models for sustainable exploration. *International Journal of Scholarly Research in Science and Technology, 2024*, *04*(01), 032–041

Onwuka, O. U., & Adu, A. (2024). Eco-efficient well planning: Engineering solutions for reduced environmental impact in hydrocarbon extraction. *International Journal of Scholarly Research in Multidisciplinary Studies, 2024*, *04*(01), 033–043

Onwuka, O. U., & Adu, A. (2024). Subsurface carbon sequestration potential in offshore environments: A geoscientific perspective. *Engineering Science & Technology Journal*, *5*(4), 1173-1183.

Onwuka, O. U., & Adu, A. (2024). Sustainable strategies in onshore gas exploration: Incorporating carbon capture for environmental compliance. *Engineering Science & Technology Journal*, *5*(4), 1184-1202.

Onwuka, O. U., & Adu, A. (2024). Technological synergies for sustainable resource discovery: Enhancing energy exploration with carbon management. *Engineering Science & Technology Journal*, *5*(4), 1203-1213.

Onyiriuka, E. J., Ewim, D. R. E., & Abolarin, S. M. (2023). An optimization technique to identify simulation assumptions for various nanofluids using machine learning. International Heat Transfer Conference Digital Library.

Orikpete, O. F., & Ewim, D. R. E. (2023). A review of noise management practice in Nigeria. *Environmental Science & Sustainable Development, 8*(1), 31-44.

Orikpete, O. F., Leton, T. G., & Ewim, D. R. E. (2020). Mathematical modeling of environmental noise generated by rotorcraft overflight. *Journal of Critical Reviews, 7*(19), 10097-10110.

Popoola, O. A., Adama, H. E., Okeke, C. D., & Akinoso, A. E. (2024). Conceptualizing agile development in digital transformations: theoretical foundations and practical applications. *Engineering Science & Technology Journal*, *5*(4), 1524-1541.

Popoola, O. A., Adama, H. E., Okeke, C. D., & Akinoso, A. E. (2024). The strategic value of business analysts in enhancing organizational efficiency and operations. *International Journal of Management & Entrepreneurship Research*, *6*(4), 1288-1303.

Popoola, O. A., Adama, H. E., Okeke, C. D., & Akinoso, A. E. (2024). Advancements and innovations in requirements elicitation: Developing a comprehensive conceptual model. *World Journal of Advanced Research and Reviews*, *22*(1), 1209-1220.

Popoola, O. A., Adama, H. E., Okeke, C. D., & Emmanuel, A. (2024). Cross-industry frameworks for business process reengineering: Conceptual models and practical executions.

Popo-Olaniyan, O., Elufioye, O. A., Okonkwo, F. C., Udeh, C. A., Eleogu, T. F., & Olatoye, F. O. (2022). Inclusive workforce development in US stem fields: a comprehensive REVIEW. *International Journal of Management & Entrepreneurship Research*, *4*(12), 659-674.

Popo–Olaniyan, O., Elufioye, O. A., Okonkwo, F. C., Udeh, C. A., Eleogu, T. F., & Olatoye, F. O. (2022). Ai-driven talent analytics for strategic hr decision-making in the United States Of America: A Review. *International Journal of Management & Entrepreneurship Research*, *4*(12), 607-622.

Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). Review of advancing US innovation through collaborative hr ecosystems: a sector-wide perspective. *International Journal of Management & Entrepreneurship Research*, *4*(12), 623-640.

Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). A Review Of Us Strategies For Stem Talent Attraction And Retention: Challenges And Opportunities. *International Journal of Management & Entrepreneurship Research*, *4*(12), 588-606.

Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). Future-Proofing human resources in the US with AI: a review of trends and implications. *International Journal of Management & Entrepreneurship Research*, *4*(12), 641-658.

Solomon, N. O., Kanchan, S., & Kesheri, M. (2024). Nanoparticles as Detoxifiers for Industrial Wastewater. *Water, Air, & Soil Pollution*, *235*(3), 1-26.

Suku, P. G., Ugwoha, E., Orikpete, O. F., & Ewim, D. R. E. (2023). Assessment of respiratory and reproductive impacts of artisanal refinery activities on male Albino Wistar rats: Implications for environmental health. *Bulletin of the National Research Centre, 47*(1), 149.

Thompson, O. A., Akintuyi, O. B., Omoniyi, L. O., & Fatoki, O. A. (2022). Analysis of land use and land cover change in oil palm producing agro-ecological zones of Nigeria. *Journal of Agroforestry and Environment*, *15*(1), 30-41.

Uduafemhe, M. E., Ewim, D. R. E., & Karfe, R. Y. (2023). Adapting to the new normal: Equipping career and technical education graduates with essential digital skills for remote employment. *ATBU Journal of Science, Technology and Education*, *11*(4), 51-62.

Usiagu, G. S., Adekoya, O. O., Okoli, C. E., Daudu, C. D., & Ekemezie, I. O. (2024). LNG as a bridge fuel in the transition to renewable energy: A global perspective. *World Journal of Advanced Research and Reviews*, *21*(2), 742-749.

Usiagu, G. S., Ayorinde, O. B., Okoli, C. E., Daudu, C. D., & Adekoya, O. O. (2024). Environmental implications of LNG usage: A comparative review of policies in the USA and Africa. *World Journal of Advanced Research and Reviews*, *21*(2), 742-749.

Uyigue, L., & Solomon, N. O. (2017). Measurement and Modelling of the Biochemical Oxygen Demand Profile of Brewery Wastewater. *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, *8*(4), 193-201.

Wiggins, J., Cox, M. F., Howard, A., Leveni, M., Cuellar-Gaviria, T. Z., & Hisey, C. L. (2023). Doing academia differently: The creation of a cohort-based postdoctoral scholars program for emerging engineering faculty. 2023 ASEE Annual Conference & Exposition.