FEDERAL UNIVERSITY OF TECHNOLOGY
MINNA

RAVE OF SMALL BUT MIGHTY NANOMATERIALS IN THE 21ST CENTURY ENGINEERING INNOVATION: WHERE ARE WE AS A COUNTRY?

BY:

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Professor of Chemical Engineering

INAUGURAL LECTURE
SERIES 135

5TH NOVEMBER, 2026

FEDERAL UNIVERSITY OF TECHNOLOGY,
MINNA

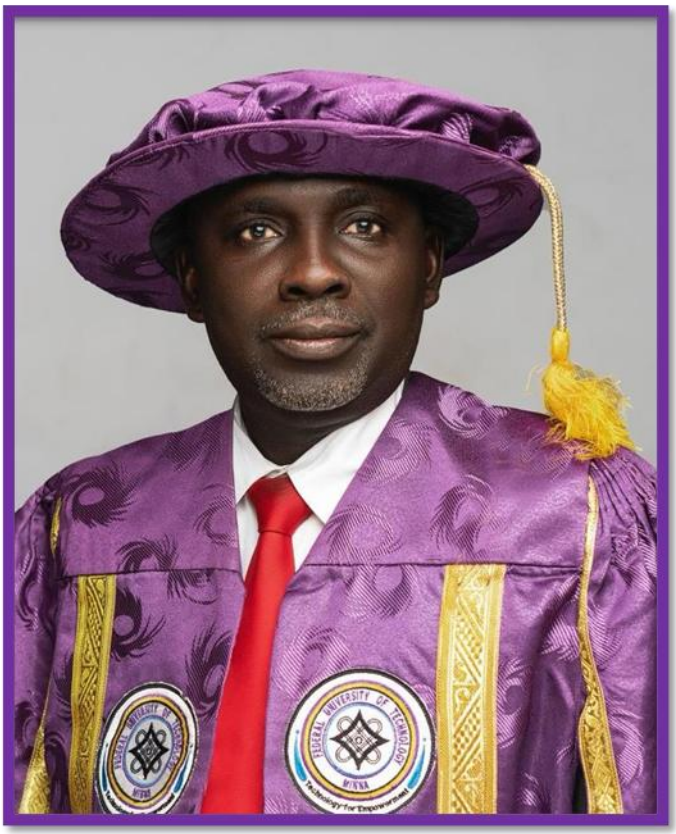
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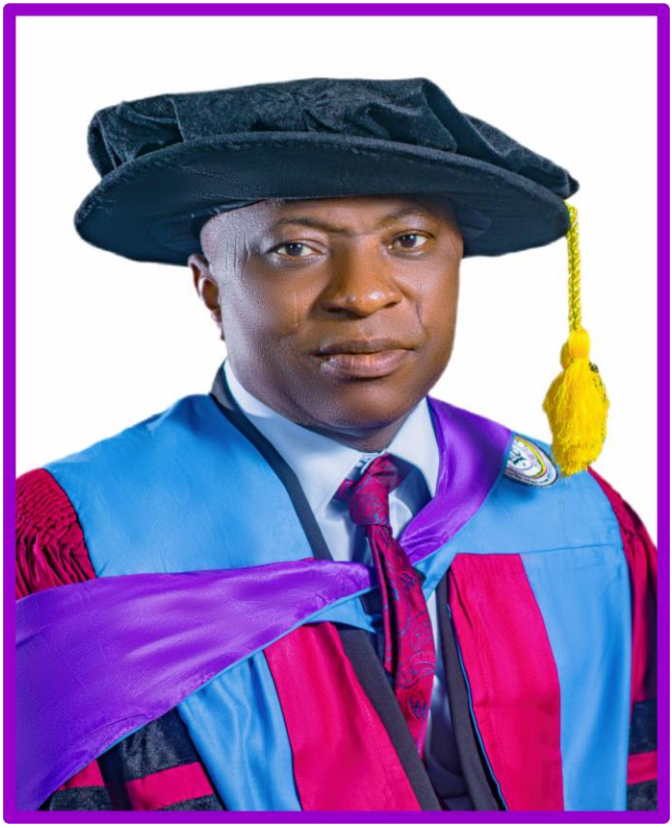
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THURSDAY 5TH NOVEMBER, 2026



Prof. Faruk Adamu Kuta
B.Sc. (UDUS), M.Tech. (FUTMIN), PhD (ATBU)
Vice-Chancellor



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Preamble

All praise and adorations are due to Allah, the Creator and Sustainer of the universe. He knows all the unseen, not even the weight of an atom escapes from His knowledge in the heavens or in the earth. Nothing is absent (unknown) from Him, not an atom's weight within the heaven or the earth or what is smaller than that or greater, except that it is in a clear register (Q34:3). No one performs an atom or molecule of goodness or bad except he reaps it. Allah said in the Holy Quran, "So whoever does an atom's weight of good shall see it, and whoever does an atom's weight of evil shall see it (Q99: 7-8)

The Vice Chancellor Sir, and the Distinguished Audience, it is important to inform this gathering that the average radius of Atoms is 0.1nm (nanometer), which indicates the spiritual importance of nanomaterials as a tool of sustainable development as compared to macro or micro materials.

Nanotechnology did not come to us by chance at the Federal University of Technology, Minna. Our approach has been calculative and intentional since our journey began some years back. Since then, it has gradually snowballed from mere curiosity, then, to what could now be termed fixation. And this has translated to meaningful contributions in specific applications, such as wastewater treatment (Adewoye *et al*, 2021; Abdulkareem *et al*, 2023; Aliyu *et al*, 2023), alternative energy development (Abdulkareem *et al*, 2012; Mudi *et al*., 2020), corrosion prevention (Ibrahim *et al*., 2021), drug delivery system (Shitu *et al*, 2017), nano-sensor, nano food packaging (Ismaila *et al*., 2025), nano detoxifiers and biomedical engineering (Medupin *et al*., 2020). Our singular lure has been to address real societal challenges with this novel technology. We simply want to view every challenge people face through the lens of nanotechnology and offer sustainable and affordable solutions.

My pre-PhD research focused on modelling and simulating the dispersion of pollutants (air and noise) from oil exploration and exploitation activities (Odigure & Abdulkareem, 2001; Abdulkareem & Odigure, 2002; Abdulkareem & Odigure, 2006; Abdulkareem et al., 2009). I was introduced to the field of Nanotechnology by my PhD supervisor (Professor Sunny E. Iyuke), with a focus-on the application of nanotechnology for fuel cell development. Since then I have been involved in the synthesis of different nanomaterials and their various hybrid for different applications. The nanotechnology group at Federal University of Technology, under my

leadership, has used this cutting-edge technology in solving Africa's developmental challenges.

As the research group leader, I was involved in the conceptualisation of the research project, the design of experiments and data analysis. I also engaged in the training of the middle-level manpower on the basic technical know-how and postgraduate students in innovative nanotechnology. This inaugural lecture titled "**Rave of Small but Mighty Nanomaterials in the 21st Century Engineering Innovation: Where are we as a country?"** focuses on my research contributions in the field of nanotechnology for sustainable development. The innovative transformation witnessed in engineering materials in the 21st century is driven by the convergence of advanced materials, nanotechnology, digitisation, advanced manufacturing and sustainable energy systems. Furthermore, nanotechnology is technological advancements that integrate smart technology, data integration, and automation to optimise materials' composition and/or process parameters, among other intriguing, efficient and performance-based components, enhanced real-time decision-making, productivity, flexibility and performance index. This core field of materials is the bedrock of my teaching and research sojourn, forming the epicentre from which my contributions to knowledge and industry resonate. This inaugural lecture will dissect nanomaterials and examine their relevance as a cornerstone of nanotechnology for modern engineering innovation, with particular emphasis on their potential application in Nigeria to solve domestic and industrial challenges via feasible implementation.

1.1 Background

Chemical engineering is a branch of engineering that deals with the development and optimisation process that transforms raw materials into useful products through chemical, physical or biological transformation. Chemical engineering involves the application of principles from biology, physics, mathematics, chemistry, and economics for the development of efficient industrial processes and equipment used in the large-scale production of goods. The branches of chemical engineering include: process engineering, petroleum/petrochemicals, pharmaceuticals, biochemicals, materials science, polymers, nanotechnology and nanoscience.

Nanotechnology is the science and technology of very small objects and phenomena on the scale of a few to about 100 nanometers involving

individual atoms, molecules, single electrons, and single photons (Baba *et al*., 2026). Nanotechnology includes both the engineering of small-scale as well as understanding of basic physical and chemical behaviour and phenomena of these objects. Nanotechnology is therefore, a combination of science and technology used to modify and control matter at a very small scale. Nanotechnology is important firstly because it has the potential to make optimal use of material and secondly because matter, when modified at the nanoscale, can have extraordinary and useful properties which have never been observed before. Using these properties will have the potential to create materials with benefits to health, welfare and prosperity of mankind. The global activity in nanotechnology is growing rapidly, driven by strong interest and investment from the commercial and public sectors, which have already seen short-term returns in different areas of application (Bankole *et al*., 2014).

Many commercially available products, such as sunscreen contains composites titanium dioxide and zinc oxide nanoparticles that were added to block the UV radiation and reduce the weight of the sunscreen. Similarly, in the textiles industry, silica nanoparticles were blended with textile materials to produce water and liquid-repellant fabrics, while the technology helped in furniture to create waterproof and less flammable furniture through coating of the furniture foam and cloth with carbon nanofiber. The concept of nanotechnology promises to deliver numerous benefits to society, and it will have tremendous potential if it can be fully harnessed; it stands to produce significant scientific and technological advances in diverse fields. Therefore, the goal of nanotechnology is to produce new materials, devices and systems tailored to meet the needs of growing range of commercial, scientific, engineering and biomedical applications opening new market and giving dramatic benefits in product performance.

1.2 Role of Nanotechnology in Industrial Revolution

The prospects and potential of nanotechnology to revolutionise various aspects of human endeavour cannot be underestimated. This informed the huge investment of the developed countries in research and development in order to promote innovation and commercialisation of nanoproducts. A Merill Lynch economist, Norman Poire (2002), considered nanotechnology as the next phase of the second industrial revolution following the information and communication technology era that may have reached its rapid growth phase by 2025 (Dutta, 2007). Figure 1 shows Norman Poire's prediction of nanotechnology potentials as compared to other major technological evolutions (Hamlett, 2008).

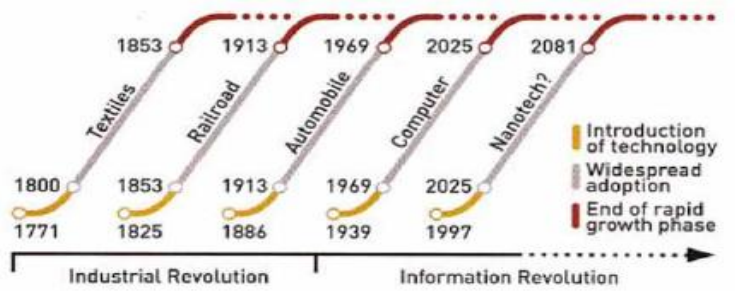


Figure 1: Trend of revolutionary forces from 1771 till date (Hamlett, 2008).

The science and technology of nanomaterials is still a baby technology but has received much attention from researchers, especially within the last twenty years. Its application in medicine, electronics, catalysis, sensors, energy, mechanics, and many other fields has also become widespread (Bhattacharjee, *et al*., 2011). Presently, there is a gradual acceptance of nanotechnology in addressing some human needs. Figure 2 shows that major developed countries of the world like Europe, Japan and the U.S.A. are spending heavily to fund nanotechnology research for possible applications in various areas (Almuhanna *et al*., 2009).

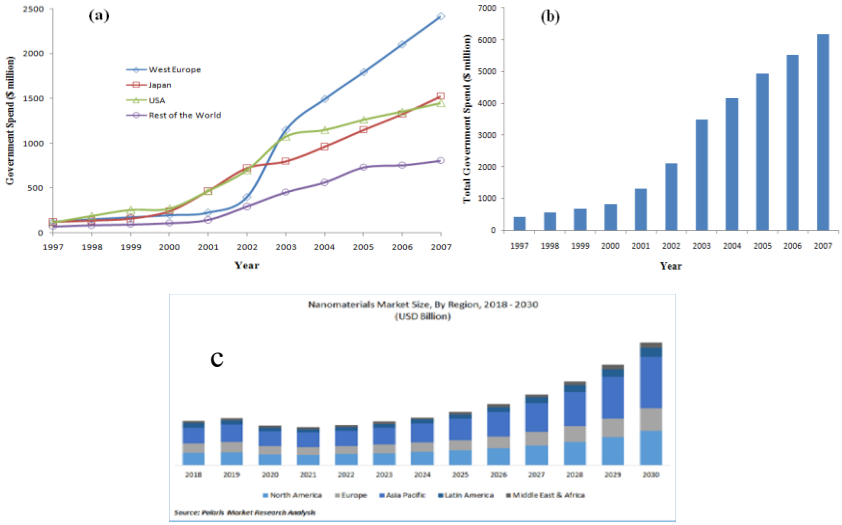


Figure 2: Global government-funded nanotechnology (1997 – 2007) (a) by countries, and (b) total (c) Market size (Almuhanna *et al.*, 2009).

The year 2001 marked the launching of National nanotechnology initiatives in the United States (US) and Japan, with a sudden increase in nanotechnology funding in both countries. The European Union (EU) also increased its nanotechnology funding in 2003 as it launched its nanotechnology initiative. In 2006, the total nanotechnology funding in the rest of the world was about half of what the US and Japan invested individually on the growing nanotechnology (Almuhanna *et al.*, 2009). Recent developments have shown that the nanotechnology market has progressed through three phases: research and development, the introduction of novel exceptional nanomaterials, and their conversions into bulk commodity status. Higher-value-added applications are now possible due to a developed supply chain and stable commercial availability of nanomaterials (Almuhanna *et al.*, 2009). The higher-value products resulting from the commoditization and consolidation of nanomaterials were projected to reach a market of US$1.5 trillion in 2015 (Almuhanna *et al.*, 2009). Today, several countries have strategic nanotechnology plans for nanotechnology research, development and commercialisation in order to reshape their future economy. The investments in nanotechnology have been dominated by government (public) funding, but there has also been a progressive growth in private funding of nanotechnology in some parts of the world, especially the US, Europe and Japan. Before 2010, about 35 countries were reported to have announced their national Nanotechnology plans and appropriated funds for them (Almuhanna *et al.*, 2009). It is worth mentioning that private funding for nanotechnology cannot thrive without initial government support. Though, private funding initially lagged behind public funding for nanotechnology, it has been anticipated that private funding would surpass government expenditures in the next few years (Almuhanna *et al.*, 2009).

Presently, nanotechnology has generated diverse awareness and attention and stands as one of the foremost alternative modern technologies of the 21st century (Bankole *et al*., 2014). Egypt, South Africa, Tunisia, Algeria, and Morocco have been reported to invest substantially in nanotechnology R&D in Africa. As of 2019, South Africa had twenty (20) nanotechnology patents (2015–2019) with the USPTO, developed eleven (11) nanotechnology standards. Despite the essential benefits of nanoscience and nanotechnology, Nigeria is slow to adopt nanotechnology initiatives and strategies to improve her socio-economic development and to transform important sectors.

Although, Nigeria was considered the second most active in nanoscience and nanotechnology in sub-Saharan Africa after South Africa over the past 10 years, Nigeria's participation in the global nanotechnology market remains a dream (Batta *et al.,* 2014). In Nigeria, nanotechnology research has been described to be at low ebb, characterised by a lack of state-of-the-art equipment to study nanomaterials in detail, and this limits the type of investigations carried out by researchers, mainly on the synthesis of nanoparticles and related works on nanocomposites and polymers.

There are reports of a national initiative on nanotechnology in Nigeria, but the country needs to take a more proactive stance in addressing its lingering problems in areas of medicine/therapy, energy, biotechnology and potable water (Tobin & Dingwall, 2010). During the Nigeria International Conference on Zeolite held in Abuja, Professor Joydeep Dutta emphasised that Nigeria can use nanotechnology to address challenges in the oil and gas industry to boost its national economy (Gabriel, 2014). Adopting this technology in natural gas and other allied industries will enhance the efficiency of higher-value products while reducing materials and energy consumption, emissions, material degradation and work-related operational risks. Dutta further announced that the direct removal of bacteria from contaminated water has become possible in developing countries using nanofilters. The National Agency for Science and Engineering Infrastructure (NASENI) in Nigeria identified nanotechnology as one of the key emerging areas in which Nigeria lacks expertise (Batta *et al.*, 2014). The agency was charged with the responsibility to key into the global network of research and development efforts in nanotechnology (Batta *et al.*, 2014).

Nigeria’s nanotechnology and advanced materials programme including the establishment of a proposed National Centre for Nanotechnology and Advanced Materials has not yet taken off, but NASENI is presently drawing up a road map and business plan in the new domains of nanomedicine, nanoporous and nanostructured materials, and in nanoelectronics. Four NASENI programmes that are currently running under the Nigerian nanotechnology initiatives include: (a) Nanotechnology visiting researchers’ scheme with research facilities located at Engineering Materials Development Institute (EMDI), Akure; (b) Nanoparticle production workshop and training; (c) Africa-Materials Research Society (A-MRS) executive meeting; and (d) Nanotechnology research grant. However, it can be observed that Nigeria’s nanotechnology research also suffers from coordination. There are

independent researchers working in this field whose efforts are not harnessed or adequately communicated. An instance is the successful production of carbon nanotubes (CNTs) and Tungsten Trioxide (WO_3) of different grades by a team of nanotechnology researchers at the Federal University of Technology, Minna (Asishana, 2014). Only a few research groups such as those at Ladoke Akintola University of Technology, Ogbomoso, University of Nigeria, Nsukka, Federal University of Technology, Minna and Federal University, Oye-Ekiti have organised conferences/workshops on nanotechnology. At the continental level, Egypt is the largest contributor of nanotechnology publications, followed by South Africa, Tunisia and Algeria (see Figure 3). Nigeria recorded the fastest growth between 2010 and 2019 (approximately 900 per cent), followed by Egypt (400 per cent) and Tunisia (364 per cent).

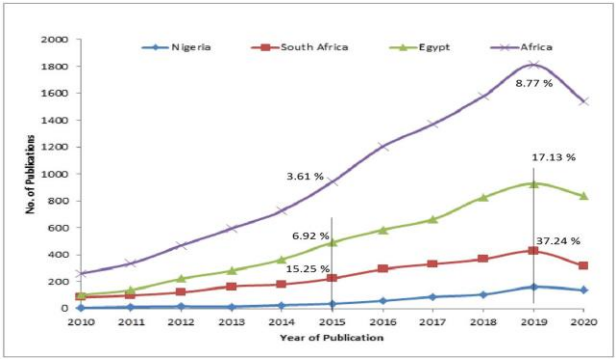


Figure 3: Nigeria, Egypt, South Africa, and Africa in nanotechnology publications (Lateef *et al*., 2021)

This inaugural lecture considers the key challenges related to the adequate personnel and state-of-the-art research infrastructure required for sustainable capacity building in the area of nanotechnology in Nigeria. There is a need for Nigeria to strengthen its local network of nanotechnology organisations and research teams, and to invest in nanotechnology with the view of boosting its future economy through adequate, committed government funding and strategic nanotechnology initiatives.

1.3 Nano industry and Nanoproducts

Nanotechnology is an emerging interdisciplinary field of research that draws on expertise across engineering, physics, biology, chemistry, mathematics, medicine, and information processing. The summary of recent advances in nanotechnology is presented in Table 1

Table 1: Recent Advances in Nanotechnology

	Applications	Contributions
Nanomedicine	Smart drug-delivery systems, including nanoparticles that can target specific cells and tissues, enhancing treatment efficacy and reducing side effects.	Targeted cancer therapies, personalised medicine, gene therapy.
Nanoelectronics	Quantum nanodevices, such as quantum dots and nanotube-based transistors, resulting in faster, and more efficient electronic components.	High-speed computing, advanced sensors, quantum communication systems.
Quantum Nanotechnology	Integration of quantum mechanics with nanotechnology to create devices with novel properties, enabling advancements in quantum computing and secure communication.	Quantum computers, secure data transmission, quantum cryptography.
Energy Applications	Energy storage and conversion, including nanostructured electrodes for batteries and supercapacitors, and enhanced photovoltaic cells.	Efficient energy storage systems, improved solar energy harvesting.
Environmental Remediation	Water purification, such as nanostructured filters and photocatalysts that degrade pollutants.	Water treatment, air purification, soil decontamination.
Nanotechnology in Materials Science	Creation of nanocomposites that combine nanomaterials with bulk materials to enhance properties like strength, flexibility, and conductivity.	Lightweight and durable materials for aerospace, automotive, and construction industries.
Food and Agriculture	Nanostructured food packaging that extends shelf life and nanosensor for monitoring food quality and safety.	Smart packaging, precision agriculture, enhanced food safety.
Nanorobotics	Tiny, remotely controlled nanobots capable of performing complex tasks, such as targeted drug delivery and minimally invasive surgeries.	Medical treatments, environmental monitoring, industrial applications.
Nano-ethics and Safety	Research into the ethical implications and safety concerns of nanotechnology, including potential environmental and health impacts.	Development of regulatory frameworks, and public health policies.
Advanced Nanoscale Imaging Techniques	New imaging methods, such as advanced electron microscopy and scanning probe techniques, enabling visualisation of nanostructures at unprecedented resolution.	Materials characterisation, biological imaging, nanofabrication.
Nanotechnology in Space Exploration	Lightweight, durable spacecraft components and advanced sensors for space missions.	Spacecraft construction, radiation shielding, extraterrestrial exploration.
Nanotechnology in Clean Energy	Clean energy applications, including efficient solar cells and hydrogen production through photocatalysis.	Renewable energy generation, sustainable fuel production

Nanoengineering is now considered a catalyst for improving the functionality of some products, with impacts on production and processes in modern industries. Carbon nanotubes body armour, surface protection materials, solar panels, food products and packaging, transdermal patches and bandages are some of the nanoproducts currently available in the market. Common nanoproducts include sunscreen, clothing, furniture, adhesives, coatings for car paint work, tennis balls, and computers. Nanotechnology offers significant benefits for sustainable development, including cost-effective renewable energy utilization, early environmental remediation, low-energy and waste-producing devices, lighter yet stronger nanomaterials, early disease detection for preventive care, and smaller, precise, and highly sensitive monitoring tools. Other benefits are found in agriculture such as food security and soil analysis; the cosmetics and communication industries; sanitation; and environmental remediation, as shown in Table 2. Despite the recognition of nanotechnology as a tool for the industrial revolution, its teaching and research are still seriously lagging behind, especially in Nigeria.

Table 2: Selected Commercial Nanoproducts and Their Manufacturers

Nano Product (Nanomaterial)	**Manufacturer/ Company**	**Country/ Headquarters**	**Typical Application**
Silver Nanoparticles	American Elements	United States	Antimicrobial, coatings, electronics, catalysis, and medical devices
Silver Nanoparticles (custom engineered)	NanoComposix	United States	Biomedical research, diagnostics, sensors, and antimicrobial materials
Silver Nanopowder	Nanoshel LLC	United States/India	Conductive inks, electronics, coatings, and catalysts
Gold Nanoparticles	U.S. Research Nanomaterials	United States	Biomedical imaging, biosensors, and drug delivery
Titanium Dioxide Nanoparticles (Nano TiO_2)	Evonik Industries	Germany	Sunscreens, photocatalysts, coatings, and self-cleaning surfaces
Nano Titanium Dioxide	Croda International	United Kingdom	Cosmetic formulations and UV-protection materials
Quantum Dot Nanoparticles	Nanoco Technologies	United Kingdom	Display technology, lighting, and optoelectronics
Silver Hydrosol Nanoparticles (SilverSol)	American Biotech Labs	United States	Medical devices, dental disinfectants, and antimicrobial treatments
Tungsten Disulfide Nanoparticles (IF-WS_2)	ApNano	Israel/United States	Industrial lubricants, coatings, and high-performance composites

2.0 My Research Contribution

Cutting-edge technology has been employed in nanotechnology research to address Africa's development challenges. This includes the synthesis, characterisation, and application of nanoparticles derived from various sources for uses such as wastewater treatment, alternative energy, composite materials in engineering, agro-allied and aqua feed processes, catalysis, entrepreneurship, training, curriculum development, and nanotechnology awareness programs. For this inaugural lecture, I will specifically focus on nanoparticle synthesis and characterisation, as well as nanotechnology applications in wastewater treatment, alternative energy, and biomedical composite materials.

2.1`Synthesis of nanoparticles

In this area of research, my research team and I have used catalytic vapour deposition method, chemical synthesis methods and green/biological methods to synthesise carbon nanoparticles (Multiwall carbon nanotubes, carbon Nanofibers and carbon Nanoballs) (Abdulkareem *et al*., 2017; Mudi et al., *2019*), silver oxide nanoparticles (Alaya-Ibrahim *et al.*, 2020), iron nanoparticles magnetite nanoparticles (Baba *et al*., 2026), titanium oxide nanoparticles (Mustapha *et al*., 2021), copper oxide nanoparticles, zinc nanoparticles, zinc oxide nanoparticles (Adamu *et al*., 2026), tungsten oxide nanoparticles, nanoclay, graphene, graphene oxide, magnesium oxide nanoparticles, cobalt nanoparticles and nickel nanoparticles. Composites of these nanoparticles on various supports have also been synthesised for various applications.

2.1.1 Synthesis of carbon nanotubes

Prior to the synthesis of CNTs by the Chemical Catalytic Vapour Deposition method, the catalyst employed was synthesised by the wet impregnation method. Different types of catalysts were developed for the production of carbon nanotubes, the journey started with the development of monometallic catalyst (Fe, Ni, Co) on different support (Al_2O_3, $CaCO_3$ and Kaolin), the success of development of monometallic catalyst led us to the production of bi-metallic catalyst [(Fe/Co), (Fe/Ni)] on $CaCO_3$ and Kaolin support (Bankole *et al*., 2018). We concluded research in this area with the development of tri-metallic catalyst (Fe/Ni/Co) on Kaolin support. The quality of the prepared catalyst was examined for its morphology, microstructure, elemental composition, surface chemical properties, thermal stability, surface area, and

mineralogical phase by HRSEM, HRTEM, EDS, TGA, FTIR, BET and XRD. Microscopy analysis of Fe/Co on Calcium Carbonate support revealed successful dispersion of Fe and Co particles onto $CaCO_3$ support while XRD patterns confirmed the presence of highly active crystalline mixed oxide ($CoFe_2O_4$) as the dominant phase. A wide-angle X-ray diffraction (XRD) technique was used to identify phases present in the final catalyst sample, as well as to perform texture analysis and measure crystallite size (Figure 4a). The speculated phases are mainly Ca_2FeCoO_5 and $CoFe_2O_4$. Others were α-Fe_2O_3, γ-Fe_2O_3, Co_3O_4 and CoO distributed within the $CaCO_3$ matrix.

The HRSEM image of the catalyst, as presented in Figure 4b, shows that the clustered solid catalyst material is near-spherical in geometry and highly crystalline. The agglomerates observed in the HRSEM images may be attributed to drying during sample preparation. In the HRSEM micrograph, micropores are evident in the catalyst, indicating proper dispersion of Fe and Co nanoparticles on the $CaCO_3$ support and the presence of minute voids within the composite.

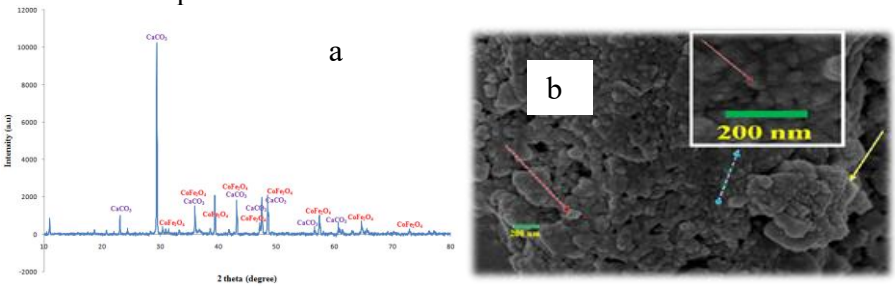


Figure 4 (a) XRD of the bi-metallic catalyst (b) SEM image showing nanoparticles of Fe and Co dispersed on $CaCO_3$ support

In addition to the SEM/EDX analysis, a more precise and accurate study of the Fe-Co/$CaCO_3$ morphology was conducted using high-resolution transmission electron microscopy (HRTEM). Figure 5 shows highly crystalline phases dispersed in the whitish $CaCO_3$ support matrix. The crystalline phase in the HRTEM is evidence of possible formation of $CoFe_2O_4$ in the final catalyst.

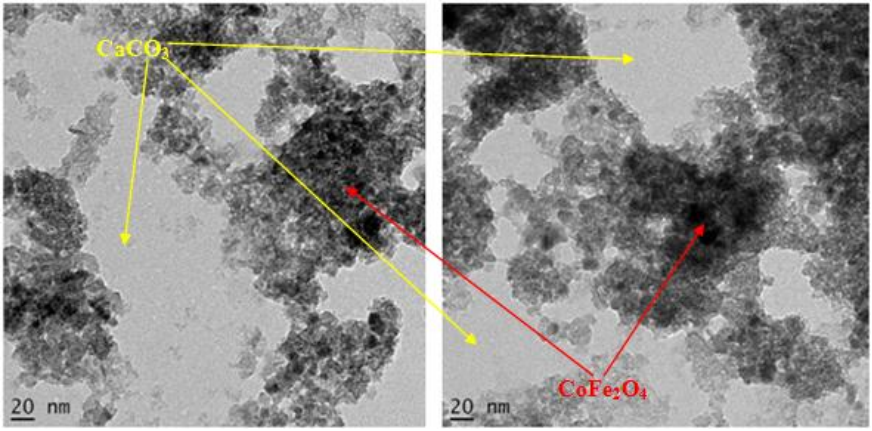


Figure 5: HRTEM images of the catalyst showing a clear view of coloured metal ions; (light brown Fe^{3+}, dark/black Co^{2+}) and white $CaCO_3$ bulk with modified crystal morphologies.

Other analyses conducted on the catalyst include Raman analysis, FTiR, SAED, TGA/DTA, EDX and DLS, (see our publications (Aliyu et al., 2017; Kariim *et al*., 2018; Oyewemi *et al*., 2019 for details). The developed catalyst was used to produce multiwall carbon nanotubes through the catalytic vapour deposition method as shown in Figure 6. The influence of process parameters such as temperature, flow rate of argon (carrier gas), flow rate of acetylene (carbon source) and reaction time on the yield of CNTs was investigated

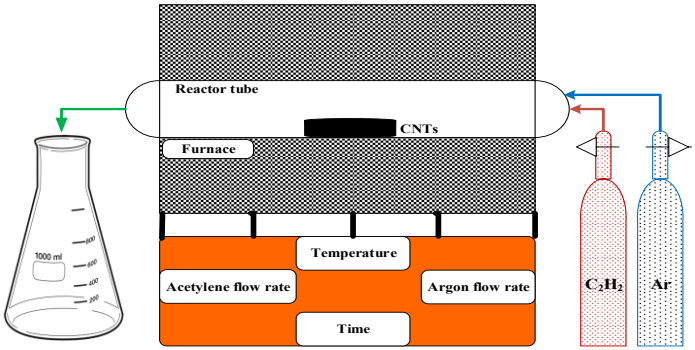
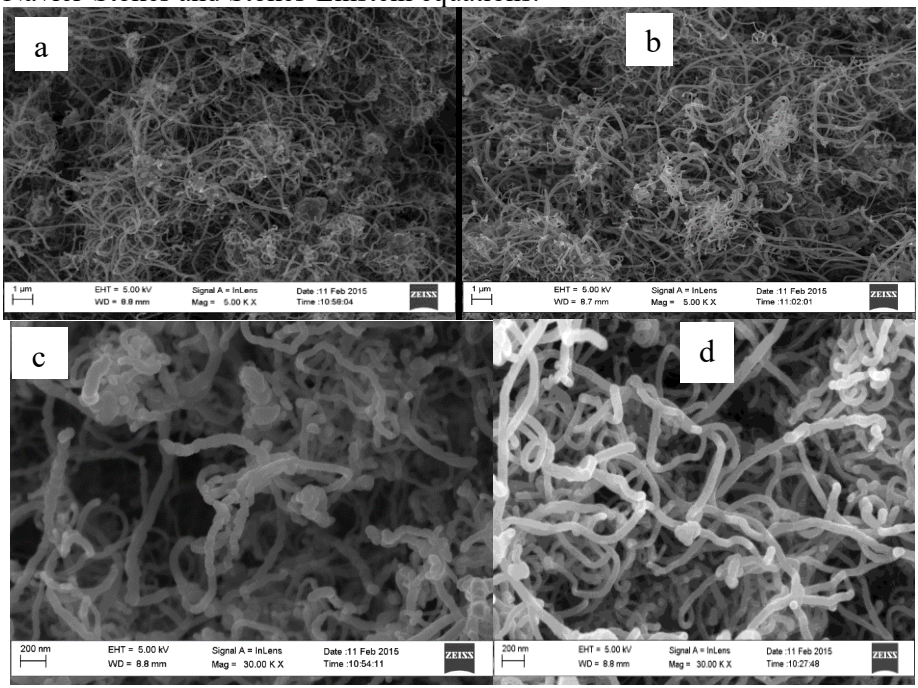


Figure 6: CVD set-up of carbon nanotubes synthesis

The as-produced carbon nanotubes were purified and functionalised for various applications. The characterisation results revealed that the CNTs and purified CNTs showed good thermal stability, surface area, functional groups, porous morphology, microstructures, crystallinity and surface oxidation states of elements. Specifically, the purified CNTs showed remarkable properties compared to the as-synthesised.

The HRSEM images (Figure 7) showed clustered MWCNTs of as-produced and purified, the images revealed that the purification methods employed was able to remove the impurities to some extent in the MWCNTs. The HRTEM images (Figure 7 e and f) revealed the outer and inner diameters of MWCNTs produced (Aliyu et al., 2017). TGA shows the high thermal stability of the MWCNTs. XRD analysis shows the characteristic broad peak of the graphitised carbon with high degree of crystallinity. Aspect ratio and length of the as-prepared and purified MWCNTs were determined from HRTEM images, and hydrodynamic diameter was calculated using the modified Navier-Stokes and Stokes-Einstein equations.



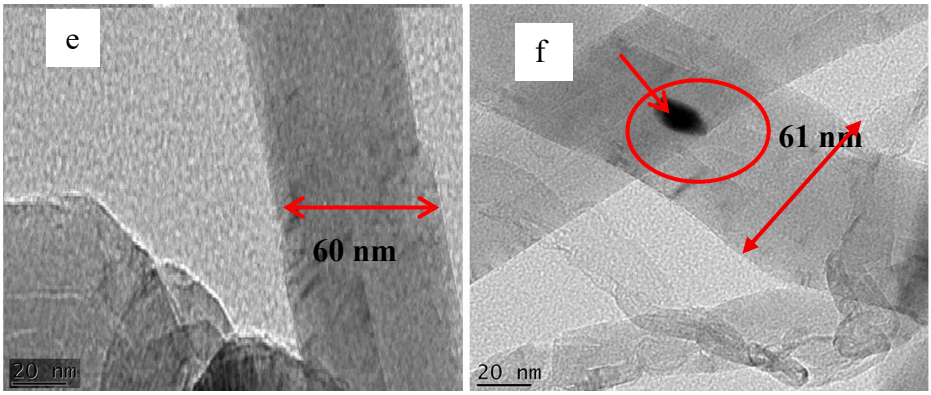


Figure 7: HRSEM image of (a & c) as-synthesized (b & d) purified carbon nanotubes (e &f) HRTEM image of purified carbon nanotubes

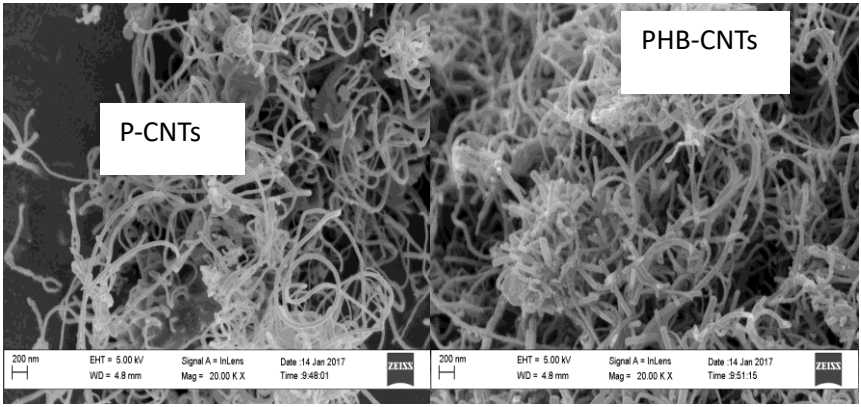
3.0 Development of Nanoadsorbents-Clay based filtration techniques for industrial wastewater treatment

Nanomaterials are highly effective separation media for water purification: they possess key physicochemical properties that enhance the adsorption process during wastewater treatment. Characteristically, nanomaterials have large surface areas, sizes, and electronic and catalytic properties, which provide opportunities to develop efficient media for wastewater sequestration. Functionalisation of nanomaterials enhances their sorption ability. In this regard, the scope of this research covers the development of nanoadsorbents from different nanoparticles, their composites, and nanofilters (from nanoclay/nanoparticles) for industrial wastewater treatment (Local metal fabrication industry, ternary wastewater, electroplating wastewater, textile wastewater, produced water).

3.1 Development of Carbon Nanotubes/Polymer composite nanoadsorbents for Treatment of Electroplating Water

In this work, we successfully developed nanoadsorbents for electroplating wastewater treatment through production and purification of multi-walled carbon nanotubes (P-CNTs) via a catalytic chemical vapour deposition method and subsequent functionalization with amino polyethylene glycol (NH_2-PEG) and its mixture with polyhydroxybutyrate (PHB) through a multi-step purification process to produce NH_2-PEG-CNTs and NH_2-PEG-PHB-CNTs, respectively (Tijani *et al*., 2024). The developed nanoadsorbents were used to treat electroplating wastewater via batch adsorption to sorb potentially toxic

metals and emerging pollutants (Bankole *et al*., 2017) as shown in Table 3. The nanoadsorbents were characterised before and after treatment of the wastewater and after thermal regeneration using HRSEM/EDS/SAED, DLS Nanozetasizer, BET, TGA/DTG, and FTIR. HRSEM of the nanoadsorbents (Figure 8) showed a homogeneous distribution of clean smooth, crystalline, interwoven tubular/cylindrical shapes and sizes, with broad polydispersity, high aspect ratio, large surface area, mesopores, and functional groups. The batch adsorption study showed simultaneous multi-metal capture from industrial electroplating wastewater, with a directly proportional relationship with contact time, adsorbent dosage, temperature, and electrostatic activity (via the positive surface charge of the nanoadsorbents (pH > pHzpc)) (Bankole *et al*., 2019). The maximum percentage removal efficiency of the heavy metals from electroplating wastewater by the nano-adsorbents are As (100 %), Pb (100 %), Cr (99.80 %), Cd (99.34 %), Ni (99.12 %), Cu (94.87 %), Fe (93.56 %) and Zn (89.26 %).The heavy metals metal removal efficiency of the nanoadsorbents is in the order of PHB-CNTs > PEG-CNTs > PEG-PHB-CNTs > P-CNTs, and the performance of the nanoadsorbents is not surface-area-specific but rather dependent on the individual water-holding capacity of each functionalised CNTs. Thus, making PHB-CNTs, the best nano-adsorbent for heavy metal removal from electroplating wastewater. They maintain stable morphology after thermal regeneration, enabling reusability. Treated wastewater can be safely reused in the electroplating industry or for other applications, such as agriculture.



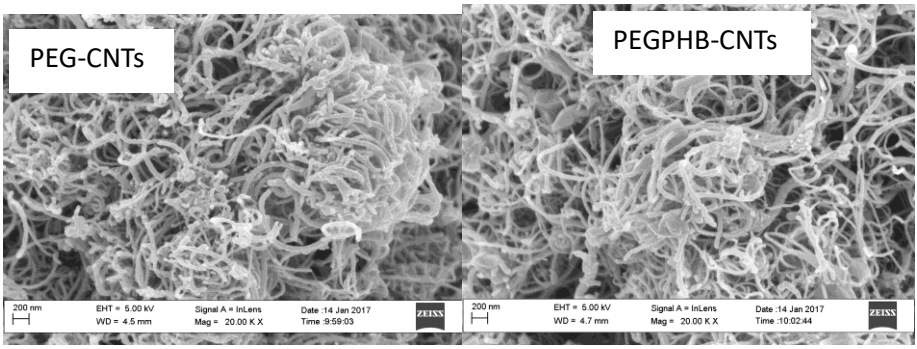


Figure 8: High resolution scanning electron microscope images of the purified and functionalized carbon nanotubes used after the treatment of electroplating wastewater

Table 3: The mean concentration of physico-chemical characteristics of electroplating wastewater (before and after adsorption process) and compared with standard permissible limit

Physico-chemical parameters	Raw value	Treatment using P-CNTS	Treatment using PHB-CNTS	Treatment using PEG-CNTS	Treatment using PEG-PHB-CNTS	LIMITS (WHO)	LIMITS (NIS)
pH	0.83	5.63	5.65	5.88	5.36	5.5-8.5	6.5-8.5
TDS (mg/L)	1915	462.3	422.1	408.7	475.7	600	500
Conductivity (μS/cm)	2860	690	630	610	710	1000	1000
Turbidity (NTU)	256	2	2	2	4	5	5
Dissolved Oxygen (mg/L)	4	5.71	5.7	5.8	5.68	5-6	-
Total Alkalinity (mg/L)	100	10	9	9	12	-	-
Nitrate (mg/L)	891	123	107	98	135	50	50
Ammonia (mg/L)	150	8.11	7.59	5.99	9	1.5/0.5	-
Chloride (mg/L)	550	40	38.5	38	49	250	-
Phosphate (mg/L)	278	6.03	5.32	4.95	6.65	0.5	-
Cyanide (mg/L)	180	1.53	1.11	1.03	1.8	0.05	0.01
Fluoride (mg/L)	305	1.21	1.09	1.05	1.33	1.5/1	1.5
Sulphate (mg/L)	1800	79	78	74	85	250/200	100
COD (mg/L)	1094	23	10	3.5	48	40	-
BOD_5 (mg/L)	1.56	1	1	0.5	1.5	10/5-7	-

Nitrite (mg/L)	5.7	0.2	0.09	0.09	0.2	3/0.05	2
Iron (mg/L)	127.5	18.01	23.115	22.12	20.125	0.3/0.2	0.3
Nickel (mg/L)	106.1	8.2325	10.1105	9.7250	9.4280	0.07/0.02	0.02
Cadmium (mg/L)	3.02	0.04	0.02	0.04	0.06	0.005	0.003
Lead (mg/L)	4.94	0.0160	0.0395	0	0	0.01/0.05	0.01
Copper (mg/L)	97.57	5.8575	6.4735	5.0065	6.6820	2/0.05	1
Zinc (mg/L)	167.6	10.09	8.215	12.12	10	5	3
Chromium (mg/L)	72.34	0.1360	0.9005	0.7850	0.5545	0.05	0.05
Arsenic (mg/L)	58.03	0	0	0.02	0.03	0.01/0.05	0.01

Key: World Health Organisation (WHO, 2008b), Environmental Protection Agency (EPA, 2007) and Nigerian Industrial Standard (NIS, 2007).

3.2 Development of Carbon Nanotubes-Silver-Polymer Nanocomposites for Industrial Wastewater Treatment

In this work, we successfully developed functionalised carbon nanotubes with silver nanoparticles, polyethylene glycol, polyvinyl acetate and clay as nano-adsorbents for the removal of the selected heavy metal ions from industrial wastewater. Agricultural wastes were also utilised in this study as a starting material for the development of activated carbon, serving as a low-cost alternative to chemical catalyst support to enhance the synthesis of low cost CNTs. The enhanced surface area, active sites, functional groups and crystallite sizes of the nano-adsorbents are the characteristic properties corresponding to their strong adsorption capacity for efficient industrial wastewater treatment (Egbosiuba *et al*., 2021a). The purified CNTs and functionalized CNTs were applied to remove 10 different heavy metals from industrial wastewater via batch and fixed bed column adsorption methods (Egbosiuba & Abdulkareem, 2021). Presented in Figure 9 is the surface morphology of the adsorbents developed from a composite of Multiwalled Carbon Nanotubes (MWCNTs) and Silver Nanoparticles (AgNPs). The higher-resolution transmission HRTEM measurement technique was used to examine the microstructure, morphology, size, and crystalline nature of the composites, as shown in Figures 9a and d. From Figure 9a, the HRTEM image of silver nanoparticles exhibited a typical spherical and ellipsoidal morphology demonstrating loosely bound particles. In addition, Figure 9d revealed the deposited silver nanoparticles on the surface of tubular network

of MWCNTs. The HRTEM analysis of silver nanoparticles and MWCNTs-AgNPs composites was measured over the 50 nm range, and the particle size distribution, presented as histogram curves, is shown in Figures 9b and e. Average particle sizes of 15.73 nm and 11.26 nm were obtained for silver nanoparticles and the MWCNTs-AgNPs composite, respectively. In Figures 9c and f, the selected area electron diffraction (SAED) pattern revealed the presence of bright ring patterns, indicating the crystalline nature of the silver nanoparticles and MWCNTs-AgNPs composites due to different planes.

Further characterization of the developed nanoadsorbents using the XRD, FTIR and XPS as presented in Figure 10 a-c respectively indicates occurrence of characteristic crystalline peaks of AgNPs observed at 2θ values of 38.32º, 44.50º, 64.59º, 77.55º and 81.81º that shows correspondence to the recorded lattice planes at (111). (200), (220), (311) and (222) of the face-centered cubic (FCC) structure of metallic silver crystal. FTIR analysis (Figure 10b) validated that Ag^{+} reduction occurred due to various functional groups: flavonoids, tannins, phenols, terpenoids and polysaccharides present in the extract. Furthermore, carbonyl groups bind to metals better than amino acids and proteins which principally forms coating layer on the metal nanoparticles surface, thereby suitably inhibiting accumulation and improving KIAgNPs stability (Egbosiuba, 2021b). To further examine the elemental and surface oxidation states of the nano adsorbent composite, XPS analysis was conducted and the result shown in Figure 10c and d depicted that the survey spectrum of MWCNTs-KIAgNPs clearly illustrated the appearance of three pronounced peaks at 284, 374 and 530 eV, indicating the nano adsorbent was predominantly composed of elemental C, Ag and O (Egbosiuba, 2021b)

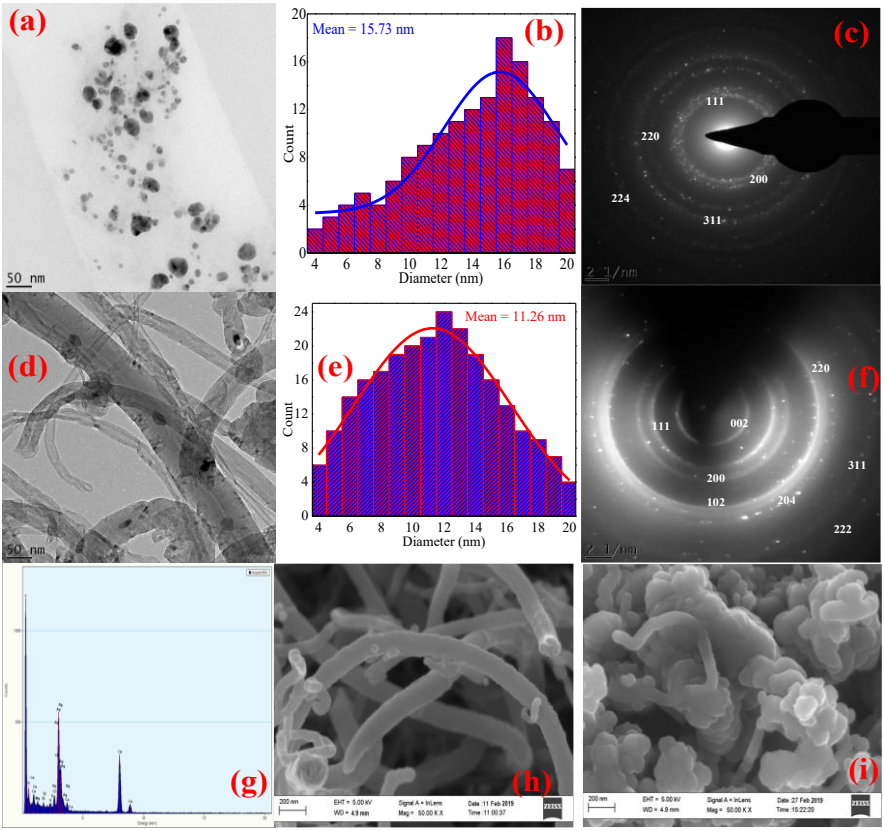


Figure 9: HRTEM image of (a) AgNPs; (b) Diameter distribution of AgNPs; (c) SAED pattern of AgNPs; HRTEM image of (d) MWCNTs-AgNPs; (e) Diameter distribution of MWCNTs-AgNPs; (f) SAED pattern of MWCNTs-AgNPs; (g) EDS of MWCNTs-AgNPs;HRSEM of MWCNTs- AgNPs (h) before adsorption and (i) after adsorption

The percentage removal efficiency of the heavy metals was in the order: Cr>As>Fe>Ni>Mn>Cu>Zn>Cd>Hg>Pb while the performance effectiveness of the nano-adsorbents was in this order: p-CNTs-Ag-Clay>CNTs-Ag>p-CNTs-Ag-PVA>CNTs>CNTs-Ag-PEG. The functionalized CNTs-Ag-Clay and CNTs-Ag performed better than other nano-adsorbents due to their higher functionality. The study shows that the nano-adsorbents can be used to remove all the selected heavy metals except Pb, Mn, and Ni in the batch process. The fixed-bed column showed the best breakthrough curves at a bed height of 6

cm, an initial concentration of 25%, and a flow rate of 5 mL/min. Interestingly, all the selected heavy metals were effectively removed below the permissible standard limit using CNTs-Ag and CNTs-Ag-Clay in fixed bed column adsorption. It can be inferred from the various analysis conducted that the developed nano-adsorbents are suitable for industrial wastewater treatment.

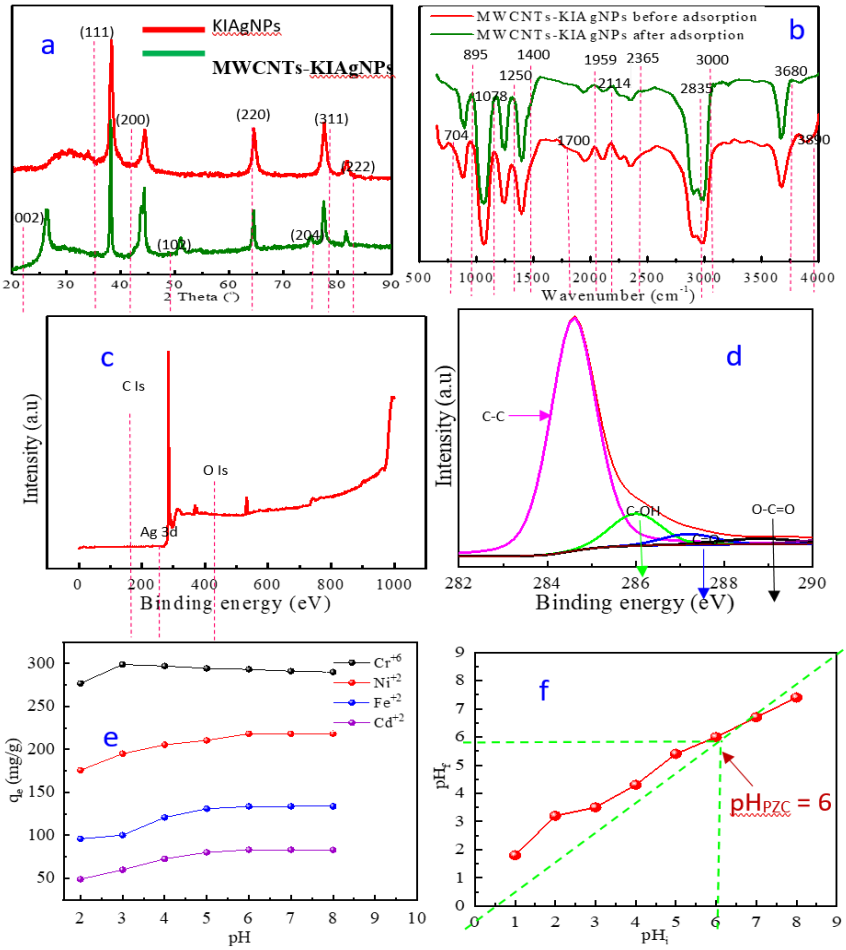


Figure 10: (a) XRD of AgNPs and MWCNTs-AgNPs; (b) FTIR of MWCNTs-AgNPs before and after adsorption; (c) XPS full survey scan spectra of MWCNTs-AgNPs (d) High resolution C 1s spectra of MWCNTs-AgNPs; (e) Effect of pH on the adsorption of metal ions by MWCNTs- AgNPs; (f) Point of zero charge pH (pHPZC) of MWCNTs-AgNPs.

3.3 Development of Nanocomposite and Nanoclay based Filtration Techniques for Electroplating and Mining Wastewater Treatment:

3.3.1 Development of Two-Stage Nanofilter for Electroplating Wastewater Treatment

A two-stage filter for industrial wastewater treatment was developed using nanoclay to continuously remove dissolved solids and heavy metals. Clay samples from four clay deposits in Nigeria (Afuze in Edo State, Ahoko in Kogi State, Ubakala in Abia State and Wase in Plateau State) were characterised for their suitability for nanoclay production. X-Ray Fluorescence (XRF), X-Ray diffraction (XRD) and Scanning Electron Microscopy (SEM) were used for the characterisation of the raw clay samples. Afuze clay was selected for the production of nanoclay based on its montmorillonite content. Nanoclay was produced using a sedimentation technique. Stokes' law was applied to produce clay particles with a hydrodynamic diameter of < 2 μm, yielding the nanoclay. The nanoclay produced from Afuze clay was activated using 2M HNO_3 at 80 °C for activation times of 30, 60, 90, 120, 150 and 180 min to improve its surface area for adsorption of heavy metals. Characterisation of the activated nanoclay using the nitrogen adsorption technique for surface area determination and SEM revealed that the optimum activation time was 150 min, and the sample was therefore chosen for further work.

To further improve the adsorption properties of the activated nanoclay, it was blended with magnetite nanoparticles. The magnetite nanoparticles were produced by the green synthesis co-precipitation method using Fe^{2+} and Fe^{3+} as precursors and aqueous extract of mango leaves as reducing agent. Optimisation of the synthesis method produced magnetite nanoparticles with a diameter of 9 nm using a precursor-to-mango extract volume ratio of 1:15 at 70 °C without stirring the reaction medium. Nanoclay-magnetite nanocomposites were then prepared by green synthesis co-precipitation method by reacting nanoclay, iron precursors and mango leaves extract in a single step. They were fired at 400 °C and 700 °C to achieve chemical and physical stability. Results from the Transmission Electron Microscopy (TEM) of nanoclay-magnetite nanocomposite indicate that the mean diameter of the magnetite nanoparticles anchored within the clay structure was 70 nm. The nanoclay (NC), activated nanoclay (AC), nanoclay-magnetite composite fired at 400 °C (MC) and nanoclay-magnetite fired at 700 °C (HC) were applied as adsorbents in batch adsorption treatment of electroplating wastewater at

contact time of 15 – 120 min in steps of 15 min; adsorbent dosage of 2 – 6 g/100ml and temperature of 30 – 70 ºC. The combined efficiency of heavy metal removal for Pb, Ni, Cu, Zn, Fe, Cr and Cd follows MC > AC > NC > HC (Table 4). The kinetic study of the sorption data indicates that the adsorption kinetics were better described by pseudo-second order kinetics than the pseudo-first order kinetics.

Table 4: Water Quality Parameters before and after adsorption treatment

Parameter	Raw Electroplating Wastewater	Treated with NC	Treated with AC	Treated with MC	Treated with HC	*Limit
pH	3.20	5.5	5.4	5.7	5.7	5.5-9
TDS (mg/L)	1,915	807	794	546	966	2,000
Conductivity (µS/cm)	2,860	1205	1184	815	1442	-
Dissolved Oxygen (mg/L)	4.00	5.5	5.61	5.54	5.48	-
Total Alkalinity (mg/L)	100	420	520	540	380	-
Nitrate (mg/L)	891	0	0	0	28.0	20
Ammonium (mg/L)	150	0	8	0	8	
Chloride (mg/L)	550	230	250	200	340	600
Phosphate (mg/L)	278	0.7	0.03	4.9	1.2	5
Cyanide (mg/L)	180	22	26	62	87	0.1
Fluoride (mg/L)	305	0.02	0.08	0.03	0.06	-
Sulphate (mg/L)	1,800	270	210	1760	400	500
COD (mg/L)	1,094	32	137	0	0	-
BOD (mg/L)	1.56	13	55	0	0	30-50
Nitrite (mg/L)	5.70	0	0	0	0	-
Lead (mg/L)	0.5158	0	0	0	0	< 1
Nickel (mg/L)	16.4566	5.313	5.5334	6.4722	8.8733	< 1
Copper (mg/L)	9.0591	4.0701	3.6853	1.825	5.3826	< 1
Zinc (mg/L)	27.0944	19.6485	18.9138	19.226	19.928	< 1
Iron (mg/L)	140.4791	40.8021	80.2749	89.6277	77.886	20
Chromium (mg/L)	1.5523	0.1335	0.1949	0.1766	0.2611	< 1
Cadmium (mg/L)	0.116	0.0819	0.0939	0.0239	0.0274	< 1

*National Environmental Protection (Effluent Limitation) Regulations. (Helmerand Hespanhol, 1997)



Plate 1: Ceramic Water Filters from Three Compositions of Nanoclay + Grog + Kaolin + Sawdust

A ceramic water filter for removal of dissolved solids was further developed from a blend of nanoclay, grog, Ubakala kaolin and sawdust (Plate I). The filter assembly (Figure 11) was tested with the ceramic water filter for removal of solids; and adsorbent from MC for removal of heavy metals. The ceramic water filter removes 81.72 % of dissolved solids from the raw electroplating wastewater (Table 5). The test indicates that each of the heavy metals in the electroplating wastewater reached the permissible limit of outlet concentration at different times of between 2 and 12 hrs. It can, therefore be concluded that the developed nanoclay-based filter can treat electroplating wastewater and be applied to similar liquid effluents.

Table 5: Physicochemical Parameters of Treated Water at One hour of Test

Parameter	Raw Electroplating Wastewater	Treated water	*Limit
pH	3.20	5.7	5.5-9
TDS (mg/L)	1,915	227.8	2,000
Ammonium (mg/L)	150	0	-
Chloride (mg/L)	550	230	600
Phosphate (mg/L)	278	2.6	5
Fluoride (mg/L)	305	0	0.0
Sulphate (mg/L)	1,800	180	500
COD (mg/L)	1,094	140	-
BOD (mg/L)	1.56	18	30-50
Carbonate (mg/L)	0	0	-
Lead (mg/L)	0.5158	0.0948	< 1
Nickel (mg/L)	16.4566	0.05592	< 1
Copper (mg/L)	9.0591	0	< 1
Zinc (mg/L)	27.0944	0.2247	< 1
Iron (mg/L)	140.4791	0.1576	20
Chromium (mg/L)	1.5523	0	< 1
Cadmium (mg/L)	0.116	0.0329	< 1

*National Environmental Protection (Effluent Limitation) Regulations (Helmer and Hespanhol, 1997)

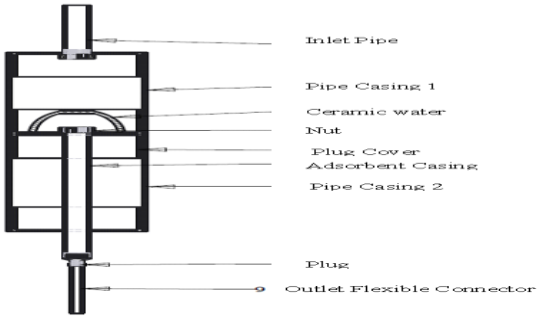


Figure 11: Nanofilter Assembly

3.3.2 Development of Silver-Titanium-Clay Nanofilter for Mining Wastewater Treatment

The discharge of untreated mining wastewater into the environment has contributed to ecosystem disruption and the spread of diseases. This arises mainly from the outrageous activities of illegal miners in Nigeria, which are linked to government policies and, fundamentally, to the underdevelopment of the mining sector. Mining wastewater has; low pH, specific colour, turbidity, foul odour, microorganisms and contains heavy *metals* like Cd, Pb, Ni, Cu, Cr, Mn, Fe, Al, Co and Zn. Exposure to lead has been reported to causes mental retardation, hyperactivity, kidney damage, dermatitis and encephalopathy (Ajala *et al*., 2026). Furthermore, exposure to Cd causes; pulmonary fibrosis, cancer of the lungs and birth defects. In addition, mining wastewater causes low yield and the death of tender plants when used for irrigation due to its low pH. Several wastewater treatment techniques, such as reverse osmosis and activated carbon adsorption, exhibit low adsorption efficiency, generate toxic sludge, and occupy space. Synthesis of nanoparticles by physical methods yields particles with low surface area, whereas chemical synthesis methods require toxic, expensive chemicals. Also, individual metallic oxide nanoparticles like TiO_2 and Ag_2O agglomerate easily during synthesis, have low surface activity and possess post-separation problems thus, they need to be immobilised on a support such as clay. Clay alone as an adsorbent is not capable of removing microorganisms that may be present in wastewater. Therefore, there is a need to prepare an effective and efficient nano-adsorbent to remove colour, odour, heavy metals and microorganisms in a single-stage process. In this study, a nanocomposite filter from kaolin base material with Ag_2O, and TiO_2 nanoparticles for the treatment of mining wastewater was

developed (Figure 12). The kaolin clay was beneficiated using a sedimentation technique for 24 h to obtain a slurry, which was sundried, pulverised and sieved with a <150 μm mesh size. The beneficiated clay was activated with 98% H_2SO_4 for 2h then washed, filtered, and oven-dried at 100 °C for 2 h to obtain acid-activated clay (AAC). Green syntheses of Ag_2O and TiO_2 nanoparticles were investigated using *Parkia biglobosa* leaf extract, with bulk silver trioxonitrate (V) and titanium isopropoxide solution, respectively. The nanoparticles of Ag_2O and TiO_2 with AAC were incorporated in different proportions onto each other to obtain different adsorbents of Ag_2O-TiO_2, Ag_2O-clay, TiO_2-clay, and Ag_2O-TiO_2-clay nanocomposites (Ajala *et al*., 2024). Other adsorbents considered for mine wastewater treatment include TiO_2 nanoparticles, beneficiated clay, and AAC. Each of the adsorbents was characterised for its functional groups, optical band, morphology/elemental composition, disparity, phase identification, surface area, and oxidation state. The mining wastewater was collected from an abandoned mine site in *Chanchaga* Local Government, Minna, Niger State. The wastewater was analysed for its metal ions composition and was found to have a high concentration of heavy metals such as Mn (II) (4.29 mg/L), Fe (III) (20.01mg/L), Pb (II) (0.98 mg/L), and Cu (II) ions (0.31 mg/L).

Other physicochemical characteristics present in the wastewater are turbidity, low pH, TDS, colour, microbes, electrical conductivity, sulphate, BOD, and COD of which are above the WHO/NIS permissible limits for drinking. The adsorbents were tested for the removal of the heavy metals by investigating the effects of time (20-180 min), adsorbent dosage (0.1-1.0 g), and temperature (30-70 □C) on the batch adsorption process. Various kinetic, isotherm, and thermodynamic models for the best adsorbent from the study were evaluated. The adsorbent with the highest percentage removal of all the metal ions was built into a water filter composed of 60% clay, 40% sawdust, and 0.042/2.46 $mg.g^{-1}$ of Ag_2O/TiO_2 nanoparticles respectively. The results obtained revealed improved crystallite size of the clay from 16.65 nm to 14.92 nm and 8.08 nm for beneficiated and activated clay respectively. The nano-synthesis of TiO_2 by *Parkia biglobossa* leaf extract yielded rutile TiO_2 with 3.45 nm crystallite size. The immobilised Ag_2O/TiO_2 on the AAC developed as adsorbents revealed the presence of hydroxyl groups at 3697.62 cm^{-1}, Si-O-Si band at 1000.68 cm^{-1}, TiO_2 band at 869.92 cm^{-1} and Ag_2O band at 461.29 cm^{-1}. The optical bands of the adsorbents confirmed the presence of Ag_2O and TiO_2 doping on the AAC with Ag and Ti in the +1 and +4 oxidation states respectively. The morphology of Ag_2O-TiO_2-clay adsorbents and

nanocomposite revealed a well-intercalated flat plate structure, with hemispherical edges and porosities that encourage maximum adsorption of heavy metals and other pollutants. The batch adsorption process justified the characterisation of the Ag_2O/TiO_2-clay nanocomposite as the most effective, among the adsorbents, with percentage removal of 96.59, 99.66, 40.26 and 96.12 for Mn (II), Fe (III), Pb (II) and Cu (II) respectively. The filter (Plate II) was operated as a single-stage process to remove selected heavy metals, turbidity, pH, colour, BOD, COD, sulphate, and phosphate. The pre-filtered wastewater was then poured into the pot and allowed to pass through the pores of the ceramic filter under gravity, as shown in Plate II. The filtered water was collected receptacle with a tap beneath the filter and analysed for heavy-metal composition and other physicochemical parameters. The fabricated filter showed a better performance than the adsorbents with percentage removals of 99.5, 100, 100, and 100 for Mn (II), Fe (III), Pb (II), and Cu (II), respectively (Table 6). Therefore, Ag_2O/TiO_2-clay nano-filter is suitable and efficient for the sequestration of pollutants from the mining wastewater.

Table 6: Physicochemical parameters performance evaluation by the filter

Parameter	Initial values	Final values	%Removal	WHO/EPA (2017)	NIS (2015)
Turbidity (NTU)	14.54 ± 0.51	1.86±0.04	87.27	1.00-5.00	5
Phosphate (mg/L)	11.60 ± 0.63	5.09±0.01	56.21	0.10	0.10
Carbonate (mg/L)	BDL	-	-	100-500	100-500
Nitrate (mg/L)	33.01 ± 0.55	5.15±0.01	84.67	50.00	50
Sulphate (mg/L)	38.83 ± 0.15	2.30±0.1	94.08	100	100
BOD (mg/L)	1.04 ± 0.18	1.00±0.00	78.12	Not specified	
COD (mg/L)	274.00 ± 6.00	28.00±0.58	89.78	<120	
DO (mg/L)	3.27 ± 0.01	1.00±0.00	69.41	>6.50-8.00	>6.50-8.00
Ph	5.97 ± 0.05	7.80±0.08	24.10	6.50-8.50	6.50-8.50
Total coliform (Cfu/100 mL)	$1.12x10^3$ ± 25.17	$2.78x10^2$ ±2.08	74.55	10	10
Conductivity (µS/cm)	750.66 ±53.42	425.00±1.63	45.51	<500	<500
Fe (mg/L)	20.02±0.20	0.00±0.01	100	1.00-3.00	0.3
Cu (mg/L)	0.31±0.01	0.00±0.01	100	0.05	1
Mn (mg/L)	4.29±0.01	0.01±0.01	99.74	0.05	0.2
Cd (mg/L)	ND	-	-	0.005	0.003
Ni (mg/L)	0.33±0.01	-	-	3.00	0.02

Pb (mg/L)	0.98±0.01	0.00±0.01	100	0.015	0.01
Cr (mg/L)	0.10±0.01	-	-	0.10	0.05
Colour	Dark	Clear	100	Clear	Clear
Odour	Offensive	Odourless	100	Odourless	Odourless

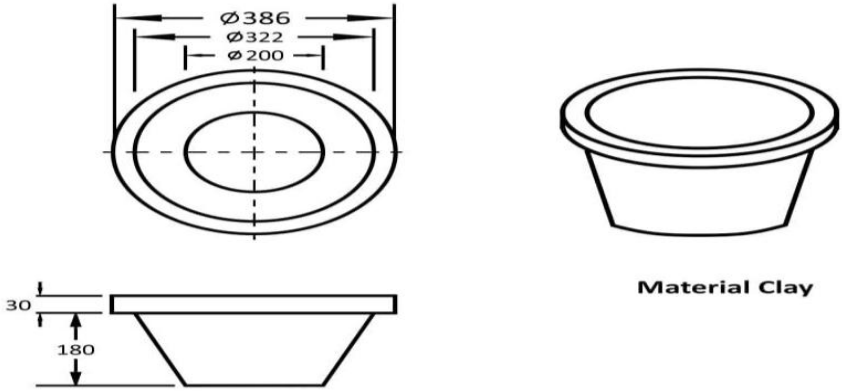


Figure 12: Design of Big Size Ceramic Filter



Plate II: Pictorial representation of (a) Assembled filter for the wastewater treatment, (b) residue, (c) mining wastewater, and (d) treated mining water

3.4 Nanotechnology for Alternative Energy (Fuel Cell) Development

3.4.1 Development of Proton Exchange Membrane for Fuel Cell

The demand for alternative energy sources is very high, and the challenge lies in developing new technologies that are both efficient and environmentally friendly, as alternatives to fossil fuels (Abdulkareem *et al*., 2016). A fuel cell, especially a proton exchange membrane fuel cell, is considered the most promising alternative method for converting and utilising energy, with many benefits, including low pollutant emissions, sustainability, and reliability (Afolabi *et al*., 2012). However, a number of issues need to be resolved before the proton exchange membrane fuel cell can become commercially and technologically viable. These include the membrane's durability and availability, among many other factors. In this research, proton exchange membrane (PEM) was synthesised by sulphonating locally available polystyrene-butadiene rubber using chlorosulphonic acid as the sulphonating agent. The synthesised membrane was blended with carbon nanoballs (CNBs). The synthesised membranes and the composite membranes were characterised to determine their suitability for proton exchange membrane fuel cell application. The results of various analyses conducted on the synthesised membrane show better qualities in terms of thermal stability, solvent uptake, porosity to solvent, methanol crossover and water uptake than Nafion® 112, which is the commercially available membrane (Idibie *et al*., 2010). The synthesised and composite membranes were sandwiched between two electrodes to form a membrane electrode assembly (MEA) using the hot-press method at a constant temperature, pressure, and time. The performance of the fabricated MEA was tested in a single PEM fuel cell using hydrogen as the fuel gas and oxygen as the oxidant at room temperature. The results presented in Table 7 reveals that the utilisation of sulphonated PSBR resulted in higher performance compared to Nafion® 112, while the membrane blended with carbon nanoballs exhibited a superior performance to a non-blended membrane. Hence, the chemical modification of a locally available polystyrene butadiene rubber to serve as an efficient and novel alternative to Nafion® for proton exchange membrane fuel cells is possible.

Table 7: Effects of mass of CNBs on the performance of SPSBR-based MEAs

Mass of CNBs (g)	Maximum power density (W/cm^2)	Percentage increment (%)
Nafion®112	0.067	
0	0.0737	
0.1	0.0788	6.92
0.2	0.0839	13.84
0.3	0.0931	26.32
0.4	0.0971	31.75

3.4.2 Development of Carbon Nanofibers-Based Electrocatalyst for Fuel Cell Application

The catalyst and membrane are parts of the basic unit of a fuel cell, bonded together into a single component called the Membrane Electrode Assembly (MEA), the heart of the fuel cell. Despite the widespread acceptance of fuel cells as an ideal alternative energy source that can either replace or complement fossil fuels, they remain commercially unavailable due to a few companies' exclusive control over fuel cell technology and their high-cost relative to other energy sources. It is therefore important to further optimise fuel cell technologies to make them more cost-effective, which can be achieved by applying nanotechnology to fuel cell development. For the purpose of this inaugural, emphasis will be on the application of nanotechnology for electrocatalyst development. We used the following experimental steps to develop carbon nanofibers-based electrocatalyst electrode for fuel cells application; (i) Optimised the process of iron-cobalt nanoparticles on Kaolin (Fe-Co/Kaolin) catalyst using RSM based on CCD, (ii) Optimised the process of CNFs synthesis by CVD method. The level of factors varied in RSM based CCD for optimization were reaction time, reaction temperature, argon flow rate and acetylene/hydrogen ratio flow rate, (iii)Purification of as-produced CNFs with 0.1M HNO_3 and H_2SO_4 mixture (v/v3:1), (iv) The Fe-Co/Kaolin catalyst, as produced and purified CNFs were characterized using XRD, TEM/EDX, SEM/EDX, TGA, BET and FTIR, (v) Synthesis and characterization of Pt-CNFs electrocatalyst was prepared by wet impregnation method with potassium tetraoxochloro Platinic (K_2PtCl_4) as the platinum sources, and (vi) Electrochemical activities of the developed electrocatalyst was measured with cyclic voltammetry and performance evaluation was conducted in Fuel cell stack (Mudi *et al*., 2020). Thermo-

Economic analysis of fuel cell fueled with methane and ethane was also carried out in this research (Suleiman et al., 2016)

The BET surface area, pore volume and pore size of as-produced CNFs were found to be 397.8 m^2/g, 0.162 cm^3/g and 2.88 nm respectively. After purification, the surface area, pore volume and pore size increased to 592.9 m^2/g, 0.212 cm^3/g and 3.148 nm respectively. The morphology and size distribution of as-produced and purified CNFs were examined using HRSEM, while the internal texture diameter and size distributions were measured by a HRTEM. The HRSEM images of as-produced and purified CNFs are presented in Figure 13. From Figure 13, it can be noticed that the as-produced sample contains CNFs in a winding form surrounded by impurities from kaolin was used as catalyst support. After acid treatment, the sample contains twin-twisted forms of CNFs, with homogenously entangled CNFs covering one another and growing in both length and diameter, as observed in Figure 13b (Mudi et al., 2019).

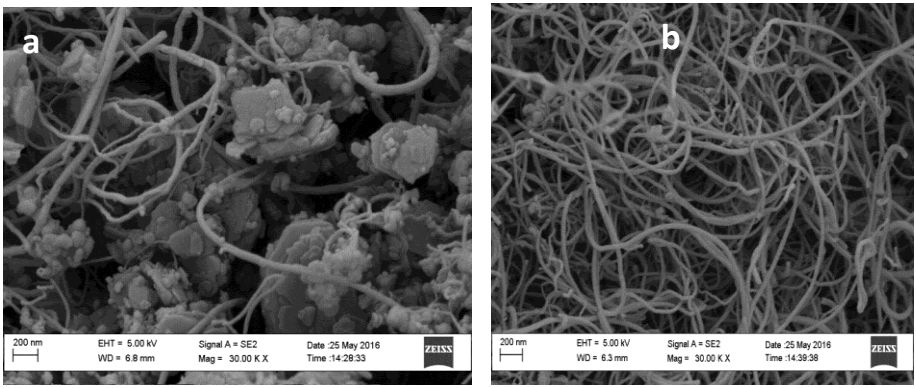


Figure 13: HRSEM image of (a) as-produced CNF and (b) purified CNF

From Figure 14, it can be seen that the nanofibers have an inner diameter ranging from 19.5 to 40 nm. The outer diameter of CNFs ranges from 25 to 100 nm, which can be controlled by adjusting the synthesis time. The image also shows that the diameter of purified CNFs remains the same as that of as-produced CNFs (Mudi *et al*., 2020).

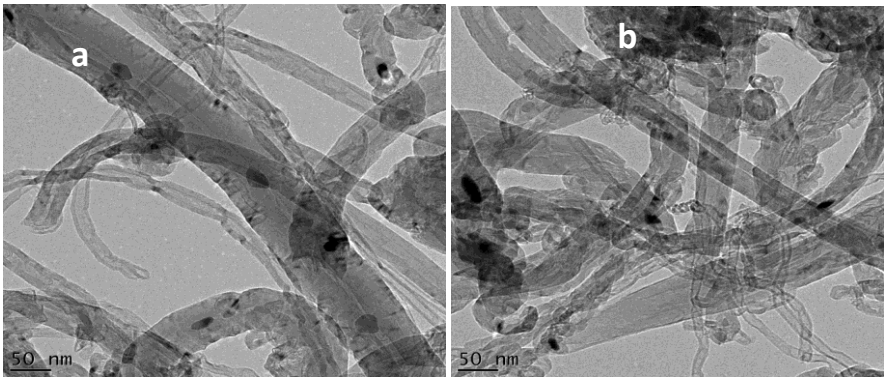


Figure 14: (a) HRTEM image of as-produced CNF showing the internal and external fibre diameter (b) HRTEM image of purified CNF showing the deformation as a result of acid treatment

The developed CNF/Pt catalyst was characterised to determine the crystalline nature using XRD, and the result is presented in Figure 15

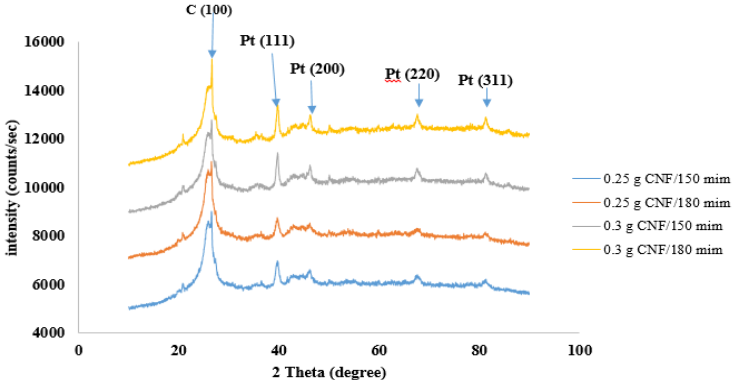


Figure 15: XRD spectrum of CNFs/Pt catalyst

From Figure 15, the XRD patterns reveals five intense diffraction peaks at 2 theta values of 26.53°, 39.94°, 46.57°, 68.24° and 81.55°. The 2 theta of 26.53° with a corresponding crystal plane (100) depicts graphitic CNFs support. Other peaks identified showed the presence of a Pt structure on the crystal planes of (111), (200), (220) and (311) respectively

Depicted in Figure 16 are the HRTEM micrographs of the developed CNFs/Pt catalyst and their corresponding EDX. The HRTEM images revealed the

presence of Pt nanoparticles scattered on the surface of CNFs. The presence of anchored Pt nanoparticles on the surface of CNFs was also confirmed by their respective EDX spectrum. The anchoring sites for adsorption of Pt nanoparticles were provided by the CNFs. The EDX spectra show that the presence of carbon indicates a graphitic nature of CNFs which serves as support and provides the anchoring sites for the Pt nanoparticles (Mudi *et al*., 2020).

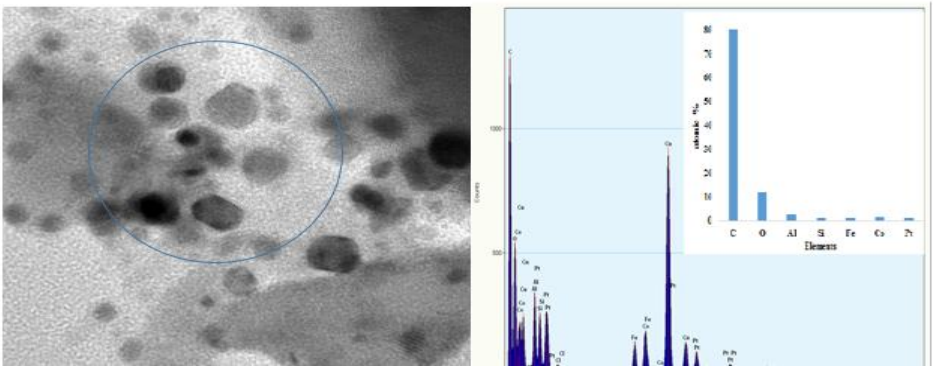


Figure16: TEM images of CNF/Pt catalyst and their corresponding EDX using 0.3 g CNFs

Furthermore, XPS analysis was used to determine the chemical state composition of Pt nanoparticles as well as the nature of the Pt compound present. The full spectrum for the catalyst showing its elemental composition is presented in Figure 17 while the spectrum for the Pt core level states is presented in Figure 18.

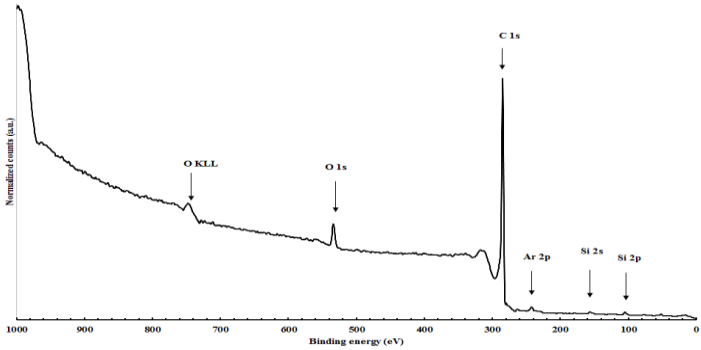


Figure 17: XPS general survey of CNFs/Pt catalyst

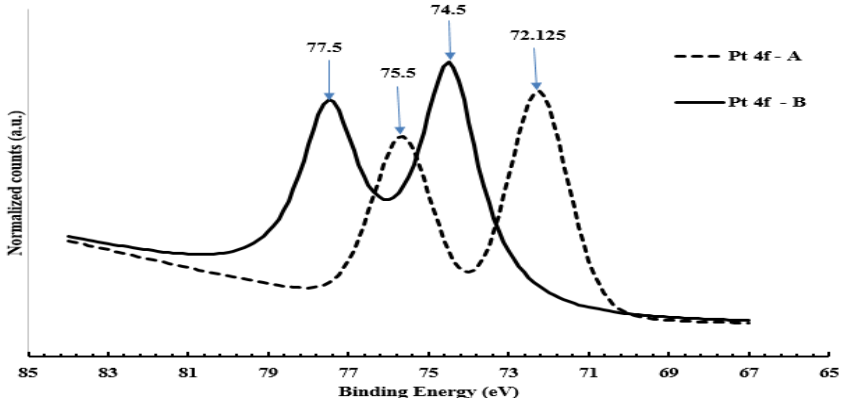


Figure 18: The spectrum of Pt 4f core level in the catalyst

The performance of the developed electrodes (CNFs/Pt composite) was evaluated by examining the influence of catalyst loading on fuel cell performance. Figure 19 shows the polarisation curve illustrating the effect of catalyst loading on cell performance at a constant fuel/oxidant ratio (1:2), operating temperature (25 °C), operating pressure (1 bar) and humidity (50%). Figure 19 shows that an increase in current density leads to a drop in cell voltage irrespective of the catalyst loading. This can be linked to the well distribution of platinum nanoparticles on the CNFs support matrix which aided the transportation of electrons within the electrodes.

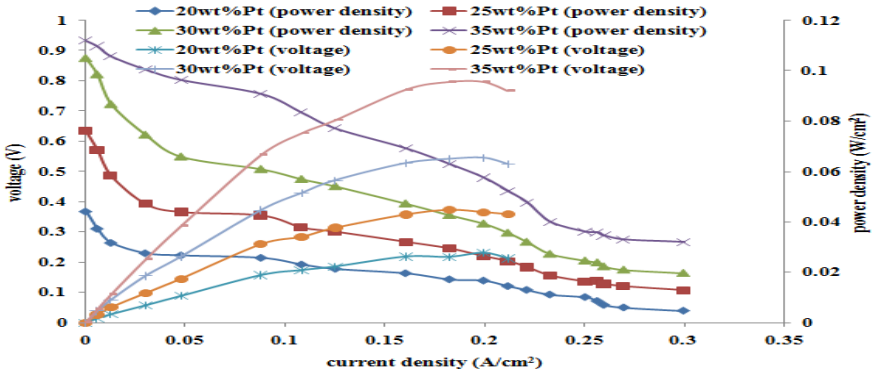


Figure 19: Polarisation curve of a single cell operated at 25 °C with H_2:O_2 ratio of 1:2

3.5 Development of Nano-Prosthetic Foot

The worldwide rate of traumatic non-fatal limb amputation is concerning. The International Diabetes Federation (IDF) predicts that the number of people with diabetes mellitus, a major cause of amputation, will rise from 8% in 2011 to 13% by 2030. In 2017, about 58 million individuals were reported to be living with limb amputation globally. Additionally, the World Health Organization (WHO) states that a limb is amputated every 30 seconds due to causes like car accidents, improper treatment of broken bones by traditional bone setters, and diabetic foot ulcers. These alarming figures highlight amputation as a pressing global health crisis. Our passion, therefore, is to see Nigerian amputees break free from the high cost, low quality and early failure associated with many existing artificial feet marketed and sold in Nigeria. We want to contribute to solving the problem posed by diabetes mellitus. While we may not be delving into the science of diabetes mellitus to design an in vivo solution to the challenge, our solution clearly addresses the drawbacks identified with existing foreign artificial feet in the Nigerian market. Over the years, we have been working to replace these expensive artificial feet with a cost-effective, more durable and more comfortable CNTs-reinforced natural rubber composite. We did this by leveraging the enormous strength of CNTs and toughness of natural rubber to produce a blend of strength and dynamic flexibility required of a material that will sufficiently mimic anatomical feet. Our team undertook a preliminary study of some existing artificial feet sold in Nigeria, with a view to developing a better product from locally sourced raw materials. After all necessary physico-mechanical, thermal and microstructure analyses were conducted on existing solutions, our search for a new solution led to the choice of natural rubber which grows well in deciduous rain forest regions of lowland tropics with temperature ranges of between 21 ^{o}C to 35 ^{o}C and a well distributed rainfall of 2000 mm. To give this polymer material the required strength, we relied on CNTs, the “wonder fibre” which our team had tested and applied in many other applications, including water purification and reinforcement of metallic materials. The choice of natural rubber was not only based on its uniqueness as a natural polymer from renewable source which is not only cheaper than polyurethane commonly used for artificial foot purposes, but also the fact that it is biodegradable. The design for the vulcanisation of the rubber is as illustrated in Table 8 (Medupin *et al*., 2019).

Table 8: Formulation of NR/MWCNTs Composites

Ingredient	Sample Code					
	NR/MWCNT-0	NR/MWCNT-3	NR/MWCNT-6	NR/MWCNT-9	NR/MWCNT-12	NR/MWCNT-15
	phr[a]					
NR	100	100	100	100	100	100
ZnO	5.0	5.0	5.0	5.0	5.0	5.0
Stearic Acid	2.0	2.0	2.0	2.0	2.0	2.0
TMQ[b]	1.0	1.0	1.0	1.0	1.0	1.0
MWCNT	0.0	3.0	6.0	9.0	12.0	15.0
MBTS[c]	1.0	1.0	1.0	1.0	1.0	1.0
Sulphur	2.5	2.5	2.5	2.5	2.5	2.5
Total	111.5	114.5	117.5	120.5	123.5	126.5

Where *a* is parts per hundred parts of rubber; *b* represents 2,2,4-Trimethyl-1,2-dihydroquinoline polymer and *c* is 2-2-dithiobis (benzothiazole)

A summary of the findings of this study is provided in Table 9. Results of characterisation of the neat natural rubber and multi-walled carbon nanotube reinforced natural rubber nanocomposites were analysed carefully before reaching the decision to select NR/MWCNT-3 in the place of other candidate nanocomposite materials. Furthermore, comparison was drawn between NR/MWCNT-3 and the selected foreign artificial foot (FAF) in order to establish the advantages of the former over the latter. This is achieved by the foregoing analysis of some of the functional properties of the materials illustrated in Table 9. While NR/MWCNT-3 offers superior dimensional stability, the FAF was found to be less stable than any of the other nanocomposites including the unfilled vulcanisate.

Table 9: Summary of findings

Properties	NR/CNTs 0%	NR/CNTs 3%	NR/CNTs 6%	NR/CNTs 9%	NR/CNTs 12%	NR/CNTs 15%	FAF
Stress at break (MPa)	0.18	0.08	0.25	0.13	0.09	0.01	-
Elastic modulus (MPa)	401.10	449.69	327.12	356.46	309.21	229.39	-
Ultimate tensile strength (MPa)	3.88	6.02	5.58	2.53	4.98	4.65	-

Hardness (Shore A)	30	38	41	38	40	45	Varied
Compression (MPa)	12.86	8.82	12.07	10.54	9.86	9.31	-
Water absorption rate (%/day)	0.157	0.127	0.133	0.146	0.130	0.137	1.300
Thickness swelling rate (%/hour)	0.11	3.60	2.33	4.18	7.15	6.52	0.19
Modulus at 100% elongation (MPa)	0.88	1.05	0.97	0.96	0.98	1.00	-
Modulus at 200% elongation (MPa)	0.65	0.85	0.75	0.79	0.82	0.85	-
Modulus at 300% elongation (MPa)	0.60	0.85	0.70	0.82	0.83	0.87	-
Temp. at maximum degradation (°C)	320.35	299.47	298.42	300.16	305.31	303.62	291.00
Onset temperature (°C)	252.12	260.01	258.34	255.70	260.99	258.34	238.17
Peak height of tan δ	2.219	2.239	2.229	2.150	2.243	2.187	-
Wear rate (cm^3/Nm)	-	0.00198	-	-	-	-	0.002896

Research achievements/ Output

Nanotechnology is a growing interdisciplinary field involving expertise from engineering, physics, biology, chemistry, mathematics, medicine, and information processing. There is a challenge due to insufficient personnel and advanced research infrastructure needed for sustainable development in nanotechnology. Currently, only a few university departments offer graduate-level elective courses on nanotechnology that cover only the basics and fundamentals, with little emphasis on applications and innovations. Nevertheless, our efforts have led to the development of a curriculum to train candidates with strong knowledge of nanoscience and nanotechnology,

focusing on new and non-traditional applications of scientific techniques to address developmental challenges. Vice Chancellor Sir and distinguished audience, I am pleased to share that our activities have helped to change the narratives; we now have students who understand and apply nanoscience concepts to solve societal issues. We are also equipping students with foundational knowledge of scientific innovation, blending academic excellence with innovative and entrepreneurial approaches to research.

Mr Vice Chancellor Sir, I am happy to report that, with the support of my collaborators, I have supervised and co-supervised 38 PhD candidates and 40 Master students to completion. Additionally, we have secured grants from University Based Research (UBR), NRF TETFund, TETFund IBR, Petroleum Trust Fund and Development Fund (PTDF), National Agency for Science and Engineering Infrastructure (NASENI), Raw Material Research and Development Council and the Federal Ministry of Mines and Steel Development, to the tune of over 1.4 Billion Naira; the details are as shown in Table 10.

Table 10: Research grant attracted to the University

Year	Local Grant (Amount (Naira) /Source)	National Grant (Amount (Naira) /Source)
2013	300,000.00 (UBR Grant)	
2014	4, 000,000.00 (TETFUND IBR)	7, 945,000.00 (TETFUND NRF)
2015	1,927,703.00 (TETFUND IBR)	
2017	4, 283,378.00 (TETFUND IBR)	
2019	3,207,725.00 (TETFUND IBR)	15,275,000. 00 (Federal Ministry of Mines and Steel Development)
2021		108, 071, 751.00 (TETFUND NRF)
2022		34,674,750.00 (PTDF)
2024	1, 975,600.00 (TETFUND IBR)	56,630,960.00 (TETFUND NRF)
2025		1,000,000,000.00 (TETFUND Commercial Farm Grant)
2026		102,000,000.00 (TETFUND NRF)

Furthermore, our collective efforts have resulted in more than 220 refereed articles published in journals with impact factors, of which 203 are Scopus- and ISI-cited journals. The breakdown of the published articles in Scopus, along with 13 patents, is presented in Tables 11 and 12, respectively.

Table 11: Article publications distribution and rating

Type of Article	Number	Quartile	Number
Article paper	146	Q1	62
Conference paper	28	Q2	40
Review paper	26	Q3	42
Book Chapter	3	Q4	4
TOTAL	**203**	NQ	55

number of nanomaterials are currently being synthesised, characterised and applied to solve societal problems globally. Therefore, nanotechnology, as a clean technology, remains an effective approach to addressing endemic problems in Africa, especially in Nigeria, related to water, the environment, food, diseases, and energy. Ultimately, integrating nanotechnology with Nigeria sustainable development policy will create high value employment and support country's transition towards a more competitive and responsible 21st century economy.

5.0 RECOMMENDATIONS

In spite of the essential benefits of nanoscience and nanotechnology, sub-Saharan Africa is yet to key into the nanotechnology initiative as a strategy for improving its socio-economic development and transformation. Many gaps still exist in nanotechnology teaching, research and development in Nigeria. One example is the lack of technology to provide Nigeria with sufficient basic necessities of life, including clean, potable water and sanitation, healthy food, an uninterrupted power supply, and a disease-free population. Based on the limitations of nanotechnology development highlighted in this lecture, the following recommendations are therefore made.

1. Teaching, learning and research in the area of nanoscience and nanotechnology that will improve the lives of people of Nigeria, who are currently facing the challenges of energy, health, environmental pollution, water sanitation and food shortage should be encouraged.

2. The goal of nanotechnology is to produce new materials, devices and systems tailored to meet the needs of a growing range of commercial, scientific, engineering and biomedical applications, opening new markets and giving dramatic benefits in product performance. The private funding for Nanotechnology research cannot thrive without government support hence, the need for the government to invest in the technology with improved strategic initiative.

3. Education, research and innovation are the critical factors required to drive the socio-economic development of any nation. In view of this, funding of nanotechnology research will facilitate capacity building through training and innovative research that will result in commercialisation of the research products.

4. Need to improve on the local network initiative of nanotechnology organisations and team of researchers in Nigeria.

ACKNOWLEDGEMENTS

O Allah, I appreciate you for the gift of life, good health, guidance, mercy and countless blessings that I cannot fully count. Thank you for providing for me, protecting me, forgiving my shortcomings and giving me opportunities to grow closer to you. You are the Most Merciful, the Most Compassionate, the Wisest and the Best of Providers. I acknowledge Allah (SWT), who taught man the use of the pen, taught man that which he knows not. All perfect praise be to Allah (SWT); Alhamudulillah for everything I have, Alhamudulillah for everything I had, Alhamudulillah for everything I will have. May the peace and blessings of Allah (SWT) be upon the prophet Mohamed (SAW), his household and companions. There have been several people, colleagues, family members, friends and many unnamed faces-all of whom have been a great help in my life.

University Management: I wish to express my profound gratitude to the University Management for providing an enabling environment that has made it possible for me to pursue my academic career and to attain this significant milestone of delivering an inaugural lecture. I sincerely appreciate the Vice-Chancellor- under the leadership of Professor Faruk Adamu Kuta and members of the University Management (The Deputy Vice-Chancellor, Academic- Professor Abdullahi Mohammed; Deputy Vice-Chancellor, Administration- Professor Uno Esang Uno; the Registrar- Mallam Danladi Mallam; the Bursar- Dr (Mrs) Hadiza Goje; the University Librarian- Professor Saka Katamba for their leadership, guidance, encouragement, and commitment to the advancement of teaching, research and community service within the University. The encouragement received from the Management has strengthened my commitment to research, postgraduate training, mentorship, and advancement of knowledge. I also acknowledge the contributions of successive university administrations (Professor Jonathan Othman Ndagi, Professor Suleiman Adeyemi, Professor Muhammed Daniyan, Professor

Mohammed Salihu Audu, Professor Musbau Akanji and Professor Abdullahi Bala), whose policies and initiatives have supported my professional growth and enabled me to contribute meaningfully to the development of the University and society at large. May Almighty Allah continue to guide the University Management, grant it wisdom and strength, and bless its efforts towards the continued growth, development, and advancement.

As I deliver this inaugural lecture, I remain deeply appreciative to the University Seminar and the Chairperson, Dr. (Mrs.) V. I. Chukwuemeka and her members for recognising and celebrating academic achievement and for providing a platform through which scholars can share their experiences, research findings and contributions to knowledge.

Teachers: To all my teachers- from my primary school, secondary school, and university- Late Prof. K. R. Onifade, Prof. F. Aberuagaba, Prof. J.O. Odigure, Prof. U.G. Akpan, Prof. M.A. Olutoye, Prof. E.J. Eterigho, Prof. S. E. Iyuke, Prof. H.C.Vz Piennar and others. Today, I want to express my heartfelt gratitude to each of you. Thank you for believing in me, teaching me, correcting me, encouraging me, and helping me become the person I am today. The lessons you taught me went far beyond the classroom. You instilled knowledge, discipline, confidence, and values that continue to guide me in life. I am truly grateful for every word of encouragement, every correction, and every opportunity you gave me to grow. Thank you for being wonderful teachers and mentors.

Classmates: GSS Old Boys (88 set: The Battalion), FUT Minna set of 96/97, Class of 96/97 Chemical Engineering and Research group at University of Witwatersrand, Johannesburg (Professor Samuel Afolabi and Dr Idibie Chris), I sincerely appreciate every one of you for being part of my educational journey. Thank you for the friendship, support, encouragement, and wonderful memories we shared throughout our time together. I am grateful for the laughter, teamwork, and kindness that made our school days memorable. May Allah (SWT) bless each of you with good health, wisdom, success, and happiness.

Friends: Bosso Campus Boys (Prof. M.T. Ijaiya, Prof. P. Idah, Prof. M. Kolo, Prof. A. S. Kovo, Prof. A. K. Jimoh, Prof. A. Muhammed, Prof. M. Saidu, Prof. A. Mustapha, Prof. R. Ojutiku, Prof. A.K. Salako, Prof. F. Akande, Prof. Musa Alhassan, Prof. Amosa Gambari, Prof. O. D Adeniyi, Prof. M. John and Dr. K. Alabi), Prof. M.T.A Ajayi, Prof. T Adejumo (Elder in Council), Prof.

J.K. Alhassan and Mrs. O. Alhassan, Dr. A. Bello, Prof. S. Dauda, Prof. A. Ojo (NEXUS), Prof. (Mrs.) Adejumo, Alhaji Abdulateef Kuranga, Engr. Yusuf Saidu, Mr Kayode Aduagba, Alhaji Kayode Adebayo, Engr. Kamaldeen Ibrahim (Dr Brown), Engr Lukuman Ibrahim, Abdulraheem Bolaji (Baba Youth, may your soul rest in peace), Alfa Salihu Akumanju, Sheikh Abdullahi Onilemarun, Sheikh Kawu Isalekoto, Sheikh Hassan Cisse, Prof. A. Abdullahi, Engr. M.B Kuranga, Engr. M. Abdullahi, Dr Olaiya (MD Archmedics Hospital), Mr. B. Tachi (yellow), all members of assembly (Isale Koto Ilorin) and Mr Oruminla and Family. Prof. Gbolahan Bolarin, Prof. A.M. Ndanisa, Prof. L.O Oyewobi, Prof. B.O Ganiyu, Prof. O.I. Oyeleke, Dr Shiru, Prof. A. Peter, Prof. O Shamsondeen, Prof. O.A Kemiki, Dr. A.A Rafiu, Dr. S.E Adebayo, Dr. S. Madeyese, Prof. H. Ibrahim, Dr S. Ojerinde, Dr. F. Ernesi, Dr. Baba. A. Musa, Dr. A. Ogaji, Mr. F.A. Omoleye, Mrs. B. Popoola (Iya ASUU), all the RPAC members. Prof M. A. Ijaya, Dr. Z. Busra, Dr. A. Olalere, Engr. Bamidele Abayomi Dada, Engr. Kazeem Adedayo, Mr Suleiman Saidu. Prof. A. M. Aibinu, Prof. L. Olatomiwa, Dr B. Salihu, Dr. J.A. Ojeniyi, Dr. T. A. Folorunso, Dr. A. S. Ahmad, Dr J. Abdullahi, Dr. (Mrs.) S. Adetoro, Dr J. Ambafi, Prof. H. Ohinze, Pastor Joshua (Chairman Gidan Madara Community), Dr Hussaini. M. Gawu, Mallam Shehu and family, Sheikh Kitab and family, Gidan Madara Community, Management, Staff and Students of Himma International College, Minna, FUT Minna, Senate members, ALUMNI of EDO State assignment, and Others. I sincerely appreciate all of you for your love, kindness, support, prayers and encouragement. Your presence in my life has been a great blessing, and I am truly grateful for every word of encouragement and every gesture of friendship. Thank you for standing by me, celebrating with me and making special moments ever more meaningful. May Allah reward you abundantly, bless you and your families and continue to strengthen the bond of our friendship.

School/Department: From the previous Deans to the current one, Prof. K.R. Onifade (RIP), Dr E.B. Oyetola, Prof. R.K. Khan, Prof. F.O. Akinbode, Prof. J.O. Odigure, Prof. O.Usifo, Prof. M.S. Abolarin, Prof. S. Sadiku, Prof. O.K. Abubakre, Prof (Mrs.). Z.D. Osunde, Prof. B.A. Adegboye and Prof. O.A. Olugboji. To all the staff of the school, academics, technologists, and registry, thank you for your outstanding contributions, friendship, and commitment to achieving excellence. My Department (Chemical Engineering and Petroleum and Gas Engineering), Prof. K.R Onifade (RIP), Prof. M Auta, Prof. A.E. Afolabi, Prof. F. Aberuagba, Prof. J.O. Okafor, Prof. J.O. Odigure, Prof. U.G. Akpan, Prof. M.A. Olutoye, Prof. O.S. Azeez, Prof. (Mrs.) E.J. Eterigho, Prof.

A.S Kovo, Prof. A. Mukhtar, Prof. O.D. Adeniyi, Prof. M.G Isah, Prof. M.U. Garba, Prof. M. Alhassan, Prof. D. Paul, Prof. (Mrs.) M.D Yahya, Dr H. Uthman, Dr. U. Musa, Dr. (Mrs.) Akanimo, Engr (Mrs.) Aisha Faruk, Engr. (Mrs.) R. Isa Abubakar, Engr. (Mrs.) Patience, Engr. U. Abdullahi, Engr. S.C. Ahmad, Mr T. Dikko, Dr M.A. Sidi, Engr. S. Ahmed, Engr. A.N. Ahmed, Engr. A. Dirisu, Engr (Mrs) E. Gana, Engr. (Miss). V. Eluwa, Mrs. F.F. Abdullahi, Mallam M. Kudu, Mallam M. Baba and Mrs P.A. Ahmed. I thank you all. FUTMIN Venture (Mrs. Atikatu, Unit staff, Water factory and FUT Guest house) and others, thank you all for your support and loyalty.

Mentor/Elders: Prof. F. O. Akinbode, Prof. K.R Onifade (RIP), Prof. (Mrs) K. Akanya, Prof. M. Galadiman, Prof. A.O. Osunde, Prof. S.O.E. Sadiku, Prof. Y. Amuda, Prof. M.T Ijaiya, I wish to express my profound gratitude and sincere appreciation to my mentors and elders in the University, whose guidance, wisdom, encouragement, and support have contributed immensely to my personal academic and professional development. Professor Abdulwahab Abdulkareem, you have been a source of inspiration, a role model and a trusted guide. I consider myself privileged to have benefited from your mentorship. May Almighty Allah reward you abundantly for your sacrifices, grant you good health and long life, and continue to bless your knowledge and efforts. I remain eternally grateful for your mentorship and the positive impact you have had on my life and career. Thank you, Sir/ma, for being an exceptional mentor and an enduring source of inspiration.

Society/Affiliations: Islamic Brotherhood (Prof. Y.A. Iyaka, Prof. A. Junaid, Prof. Y. Sanusi, Prof. K Salako, Prof. M. Ndamitso and Prof. O.S Azeez). Quranic Forum, FUT, Minna, Nigerian Society of Engineers (Minna Branch), Nigerian Society of Chemical Engineer, Minna Branch and Ilorin Emirate Descendants Progressive Union (IEDPU) Minna Branch (Alhaji M. Usman, Alhaji I.T. Yakub, Pharmacist S. Muritala, Bldr. R. Zakariyaw and others), Quranic Forum, FUT, Minna, Yoruba Forum, FUT, Minna. Academic Staff Union of University, FUT Minna, Branch. National Association of FUT ALUMNI, FUT ALUMNI Campus Chapter, Alhalal Cooperative Society, Alhaji Abdulmalik Yusuf Ajiboye (Chairman, Ajiboye Printing Press) and Family, Gidan Madara Community, and Weekend exercise club (Prof. A.S. Abdulrahman, Prof. A.S. Kovo, and Dr A. Bello). Thank you for your outstanding contributions and support.

Research Partner: Prof. J.O. Tijani, Prof. (Mrs.) O.K. Shittu, Dr (Mrs.) M.T. Bankole (RIP), Prof. O.K. Abubakre, Prof. A.S. Kovo, Prof. A.S. Asipita, Prof.

R.A Muriana, Prof. K. Isah, Prof. N. Kariim, Prof. M.M Ndamitso, Prof. A.I Ajai, Prof. M. Auta, Prof. S.A. Lawal, Prof. O. Adedipe, Prof.O.O Ogunleye, Professor T, O Salawudeen, Prof. Y. Aiyesimi, Prof. M. Jiya, Prof. (Mrs) M.D Yahya, Dr. J.B. Agboola, Dr. I.B. Akintunde, Dr. S. Mustafa, Dr E.Y Shaba, Dr. A, Yusuf, Dr. A.I. Daniel, Mrs. G.T. Yebo and Dr. P. Obasa. Mechanical Engineering Department, Materials and Metallurgical Engineering Department, Civil Engineering Department, Department of Chemistry, Department of Physics, Department of Biochemistry, Centre for Genetic Engineering and Biotechnology (STEP-B, Funded Centre of Excellence) (Prof. M.U. Garba, Prof. E.O. Ogbadoyi, Prof. O.B. Awojoyogbe, Prof. O.K. Shittu, Prof. H. Babayi, Mr I. Okworie, Mallam. A. Hamidu and Mallam A. Abdulkareem), and others. I express my profound appreciation to my research partner, whose intellectual companionship, commitment, and dedication have contributed immensely to my research journey. Beyond the publications and research outputs, I cherish the professional relationships, friendships, and mutual respect that have developed over our years of collaboration. May Almighty Allah continue to bless our partnership, grant us greater wisdom and opportunities for impactful research, and enable our work to continue making meaningful contributions to humanity and advancing knowledge.

Nanotechnology Research Group/PhD Clinic: I proudly pay tribute to our remarkable research group, whose dedication, collaboration, and commitment to academic excellence have made our research journey both productive and rewarding. Working together has been a truly enriching experience. Each member has contributed unique ideas, expertise, and unwavering support, demonstrating that great achievements are possible through teamwork. Our collective passion for knowledge, innovation, and discovery has enabled us to overcome challenges and produce meaningful research. Thank you all for your invaluable contributions, support, and commitment to excellence

Students: Dr. (Mrs.) M.T. Bankole (RIP), Dr. A. Mohammed, Dr. H.F. Akande, Prof. (Mrs.) R. Mohammed, Dr. (Mrs.) A.A. Tijani, Dr. (Mrs.). S.O. Ibrahim, Dr. R.O. Medupin, Dr (Mrs.) L.T. Adewoye, Dr. T.C. Egbosiuba, Dr. O.A. Olasupo, Dr. Y.K. Mudi, Dr. M.L. Yeriman, Dr. U.O.Madu, Dr (Mrs). S. Alaya-Ibrahim, Dr. O. Salako, Dr. S. Mustapha, Dr. B. Shehu, Dr. G.A. Kareem, Dr. O.D Chikaorama, Dr. A. Sumaila, Dr. I. Mohammed, Dr (Mrs.) M.A. Ajala, Dr (Mrs.) R.A. Abdullahi, Dr. H.L Abubakar, Dr. S.H. Abdullahi, Dr. M.U. Manko, Dr. M.M Usman, Dr. K.S. Ajao, Dr (Mrs.) J.M. Gadin, Dr (Mrs.) Z. Abdullahi, Dr. (Mrs) J.B. Ismaila, Dr. V.C. Nwachukwu, Engr. I.A.

Baba and others. I would like to express my sincere appreciation to my students for their dedication, commitment, and invaluable contributions to our academic and research endeavours. Your passion for learning, intellectual curiosity and perseverance have made supervising and working with you a truly rewarding experience. Throughout our journey together, you have demonstrated professionalism, critical thinking, and a strong commitment to excellence. I deeply appreciate your respect, cooperation, and determination to overcome challenges. I am proud of the progress each of you has made. May your research make meaningful contributions to society, and may you continue to achieve success in all your future endeavours.

Grant providers: I wish to express my profound appreciation and sincere gratitude to University-Based Research (UBR), Tertiary Education Trust Fund (TETFUND), Federal Ministry of Mines and Steel Development, Petroleum Trust Development Fund (PTDF), Raw Material Research and Development Council, and National Agency for Science and Engineering Infrastructure (NASENI), School of Chemical and Metallurgical Engineering, University of Witwatersrand, Johannesburg, South Africa, Institute of Applied Electronics, Vaal University of Technology, South Africa and others for the generous financial support provided. Your support played a significant role in facilitating my research activities and advancing the body of knowledge in my field. I am very grateful for the confidence reposed in my research and the opportunity provided to undertake studies that have contributed to academic scholarship, professional development, and the advancement of knowledge. Present and past Directors of the Directorate of Research and Innovation Development (Prof. H. Makun, Prof. M. A. Olutoye and Prof. C. E. Chima). I record my sincere thanks to the Directorate for its commitment to supporting research and innovation. May Almighty Allah continue to bless all our supporters and those associated with their efforts to promote knowledge and human development.

Family: I wish to place on record my profound appreciation to my family: Alhaji Bamidele Aileru (RIP), Professor Abdulwahab. Abdulkareem and Mrs. Memunat. Abdulkareem, Alhaji Aluko Gidado, Alhaji Abdulakreem Bolaji, Alhaji Issa Bolaji, Dr (Mrs) Fuminlayo Rihanat Olayemi, Alhaji Ayuba Abdulkareem, Alhaji Yusuf Balogun, Alhaji Ibrahim Ajao, Alhaji Sulyman Aliyu (Alakarun), Prof. M.S. Ajao, Mallam Abdullahi Koto and his wife (Iya Sallla) (RIP), the entire family of Bale Otefan and Aladi Family. Your love, prayers, encouragement and steadfast support have been a constant source of

strength throughout my life's journey. To my uncles, aunts, brother, sisters, cousins, in-laws, nephews, nieces, and every member of the extended family, I am deeply grateful for your enduring goodwill, understanding, and confidence in my aspirations. I am truly honoured to acknowledge your invaluable contributions to my journey. I pray that Almighty Allah (SWT), in His infinite mercy, will abundantly reward your kindness, grant you good health, peace, happiness and long life.

My dear lovely wife, Mrs. Bilkisu Abdulkareem, I just want to say thank you for everything you do. Your love, care, patience, and support mean more to me than words can express. You bring peace, strength, and happiness into our home, and I truly appreciate all the sacrifices you are making for our family. Thank you for standing by me through good times and difficult moments. I pray that Allah continues to bless you with good health, happiness, wisdom, and abundant rewards. May our love grow stronger every day, and may He keep our home filled with peace, mercy and joy. I love and appreciate you deeply. Thank you for being such a wonderful wife.

My dear children, Messer Abdullahi Ambali Abdulkareem, Miss. Halimat Olaitan Abdulkareem, Miss. Asiyah Ajobi Abdulkareem, Dr. Sa'ad Bashirat Abdulkareem, Mrs. Abdulhameed Azeezah Abdulkareem, Mrs Lawal Aisha Abdulkareem and Miss Habiba Toyin Abdulkareem. I want you to know how much I love and appreciate each of you. You are one of the greatest blessings Allah has given me, and I thank Him every day for your lives. I pray that Allah protects you, grants you wisdom, good health, strong faith, and success in this life and the hereafter. May he guide your steps, bless your future, and make you a source of happiness and pride to our family and to the Ummah. To my late children, Mukthar Abdulkareem and Khairat Abdulkareem, may Almighty Allah grant you entry to Al-Jannatul Firdaus. Ameen.

My Late Wife, Mrs. Ayisah Ajobi Abdulkareem: I remember you today with deep love, gratitude, and respect. Though you are no longer physically with us, your love, kindness, and beautiful memories remain forever in my heart. You were a loving wife and a source of strength to our family. Your gentle words, unwavering support, and selfless sacrifices touched the lives of everyone who knew you. The memories we shared are priceless treasures that I will cherish forever. May Almighty Allah grant you eternal peace and mercy. Ameen

Parents: Although my beloved parents (Alhaji Ambali Abdulkareem, Mrs Omomeji Abdulkareem, Alhaji Bolaji Gidado, Alhaja Sifawu Gidado and

Alhaja Halimat Gidado) are no longer here to witness this achievement, I acknowledge them with profound love, gratitude and respect. Their sacrifice, prayers, guidance and unwavering belief in the value of education laid the foundation for everything I have accomplished. Their memories have remained a constant source of strength and inspiration throughout this journey. May Allah (SWT) forgive their shortcomings, have mercy upon them, expand and illuminate their graves and grant them Al-Jannatul Firdaus. Ameen.

A BRIEF PROFILE OF THE INAUGURAL LECTURER

Engr. Professor Abdulkareem Ambali Saka was born on the 18th April, 1972 in Ilorin, Kwara State, Nigeria. He attended Ansarul Islam Primary School, Oke Aluko and Government Secondary School, Ilorin, Kwara State. His university education career started at the Federal University of Technology, Minna, where he obtained a B.Eng, an M. Eng in Chemical Engineering in 1997 and 2000, respectively and a certificate in Higher Education Assessment and Moderator Development from Rhodes University, South Africa in 2008. He obtained a PhD in Chemical Engineering from the University of Witwatersrand, Johannesburg, South Africa in 2010

Professor Abdulkareem Ambali Saka joined the services of Federal University of Technology, Minna in December 1999 as Assistant Lecturer and was promoted to the rank of Professor of Chemical Engineering in October 2017. His experience as a lecturer in Nigeria, South Africa (University of the Witwatersrand, Johannesburg and University of South Africa) and Botswana (Botswana International University of Science and Technology), coupled with the series of training programmes he attended (Teaching role, Time and stress management, Postgraduate supervision, Research writing, Voice and presentation skill, Research management, etc.), made him an enterprising academic. He has served as a member and chairman of several committees, which include: students' disciplinary committee, students' audit committee, university policies and manual advisory committee, university intellectual property policy, international institutional accreditation, committee on the establishment of commercial farms, research policy committee, member of University Journal Editorial Board, Member of Monitoring Committee on Action Plan for International Quality Review (IQR), Member of Postgraduate School Board, Member of Board of FUT Model Secondary School, Senate Representative in DRID Board, and Senate Representative in Appointment and Promotion Committee. His administrative appointments include Chemical Engineering assistant examination officer and examination officer. Deputy

Dean, School of Engineering and Engineering Technology (2012-2014), Director, Centre for Genetic Engineering and Biotechnology (STEP-B funded Centre of Excellence) (2014-2018). He is currently the Director, FUTMIN Consult and Ventures and 200-level Academic Adviser, Chemical Engineering Department.

Professor Abdulkareem Ambali Saka has taught over twenty courses at both undergraduate and postgraduate levels, supervised more than two hundred (200) undergraduate projects, supervised and co-supervised 38 doctoral candidates and 40 master's students to completion. He is the leader of the FUTMINNA Nano group, a unit under the Centre of Genetic Engineering and Biotechnology (STEP-B Funded Centre of Excellence), at the Federal University of Technology Minna. Professor Abdulkareem Ambali Saka has attracted a series of grants to the university, including the One Billion Naira TETFUND commercial farm grant. He has conducted extensive research in nanotechnology for sustainable development, resulting in 13 patents registered in South Africa, Nigeria, Europe, the USA, China, and Australia. To date, he has published more than 220 refereed articles of which 203 are Scopus-ISI cited articles; 150 of his articles are indexed in the Web of Science; 5 academic book chapters; and 27 conference proceedings. He has 8,717 Google Scholar citations with an h-index of 47, 5,428 Scopus citations with an h-index of 35, and 4,120 Web of Science citations with an h-index of 30. Prof. Saka consistently received the Federal University of Technology Vice Chancellor's commendation award for outstanding scholarly publications in Scopus-indexed journals for the years 2021-2026. He was in the top 2% of researchers worldwide for 2022-2026, as published by Stamford University, USA. Prof. Saka is a Y2 NRF-rated scientist (South Africa) (2012-2017).

Professor Abdulkareem Ambali Saka has served as a reviewer for many International and National Journals. He has served as an external examiner for postgraduate programmes in Nigeria, South Africa and Zimbabwe. He also served as a resource person for NUC and COREN accreditation numerous times. His research work is in the area of synthesis and characterisation of metal, metal oxide, and carbon-based nanoparticles for industrial wastewater treatment, drug delivery, nanofertilizers, nanofeed binders, nanosensors, and alternative energy development.

Professor Saka is a member of the Nigerian Society of Chemical Engineers, the Nigerian Society of Engineers, and a registered Engineer with COREN. He is happily married to Mrs Bilkisu Abdulkareem, and the marriage is blessed with Children.

REFERENCES

Abdulkareem, A.S and Odigure, J.O (2002). Radiative Heat Evaluation from Gas Flaring by Computer Simulation. Association for the advancement of Modelling and simulation in enterprises, Lyon France. Volume 71 No 2 Pp 19 – 35 (ISSN: 0761 – 2516). www.amse-modeling.org

Abdulkareem A. S, Afolabi A. S, Idibie C. A, Iyuke S. E and Pienaar .H.C.vZ (2012): Development of composite proton exchange membrane from polystyrene butadiene and carbon nanoballs for fuel cell application. Journal of energy procedia. Volume 14, pp 2026-2037. www.sciencedirect.com

Abdulkareem, A.S and Odigure, J.O (2006): Deterministic Model for Noise Dispersion from gas Flaring: A case study of Niger – Delta area of Nigeria. Journal of Chemical and Biochemical Engineering, Croatia Q 20 (2), Pp 157 – 164 (ISSN 0352 – 9568). http://www.pbf.hr/cabeq

Abdulkareem, A.S, Hamzat, A.W, Tijani, O.J, Egbosiuba, T.C, Mustapha, S, Abubakre, O.K, Okafor, O.B and Babayemi, A.K (2023): Isotherm, kinetics, thermodynamics and mechanism of metal ions adsorption from electroplating wastewater using treated and functionalized carbon nanotubes. Journal of Environmental Chemical Engineering 11 (2023) 109180. www.elsevier.com

Abdulkareem, **A.S**, Jimoh, A, Afolabi, A.S, E. Muzenda, E &and Okeke, A.C (2016): Predictive mathematical. modeling and computer simulation of direct ethanol fuel cell. Journal of Energy Sources Part A, Volume 38 (5), pp 635-643. www.tandf.co.uk

Abdulkareem, **A.S**, Kariim, I Bankole, M.T, Tijani, O.J, Abodurin, T.F and Olu, S.C (2017): Synthesis and Characterization of Tri-metallic Fe-Co-Ni Catalyst Supported on $CaCO_3$ for Multi-Walled Carbon Nanotubes Growth Via Chemical Vapor Deposition Technique. Arabian Journal of Science and Technology. http://link.springer.com/journal

Abdulkareem, **A.S**, Odigure, J.O and Abenege, S (2009): Predictive model for pollutant dispersion from gas flaring: A case study of oil producing area in Nigeria. Energy Sources, Part A. Volume 31 Pp 1004-1015 (ISSN 1556-7036). www.tandf.co.uk

Adamu, A, **Abdulkareem, A.S**, Kovo, A.S, Oladejo. J.O, Shaba, Y. E, Mustapha, S, Obayomi, S.K and Zhang, J (2026): Development and

adsorption performance of Ag_2O/ZnO/MWCNTs nanocomposites for effective removal of selected heavy metal ions from irrigation water. Cleaner Water 6 (2026) 100242

https://doi.org/10.1016/j.clwat.2026.100242

Adewoye, T.T, Ogunleye, **Abdulkareem**, **A.S**, Salawudeen, T.O and Tijani, O.J (2021): Optimization of the adsorption of total organic carbon from produced water using functionalized multi-walled carbon nanotubes. Journal Heliyon, Volume 7 (e05866), pp 1-15. www.cell.com/heliyon

Afolabi, A. S, **Abdulkareem, A. S,** Iyuke, S. E and Pienaar, H.C.vZ (2012): Performance and Kinetics of Pt-CNT catalyst electrodes in a PEM fuel cell. Journal of material research. Vol 27 (11), pp 1497-1505 www.Journals.canbridge.org

Ajala, A.M, **Abdulkareem**, **A.S**, Kovo, A.S, Tijani, O.J and Ajala, O.E (2024): Synthesis of Ag_2O- TiO_2- Kaolinite Clay Nanocomposite for Efficient Removal of Mn^{2+}, Fe^{3+}, Cu^{2+}, and Pb^{2+} and Pathogens in Mining Wastewater. Journal of Water, Air and Soil Pollution, 2024) 235:42. http://link.springer.com/journal

Alaya-Ibrahim, S, Kovo, A.S, **Abdulkareem**, **A.S**, Adeniyi, O.D and Yahya, M.D(2020): Development of nano-silver doped zeolite A synthesized from Nigerian Ahoko kaolin for treatment of wastewater of a typical textile company. Chemical Engineering Communication. Volume 207 Number (8), pp 1114-1137. www.tandf.co.uk

Aliyu A, **Abdulkareem A.S**, Kovo A. S, Abubakre, O. K, Tijani, O. J and Kariim I (2017): Synthesize multi-walled carbon nanotubes via catalytic chemical vapour deposition method on Fe-Ni bimetallic catalyst supported on kaolin. Carbon Letter, Volume 21, pp 33-50 www.koreascience.or.kr/journal

Aliyu, S **Abdulkareem, A.S**, Tijani, O.J, Mustapha, S, Egbosiuba, T.C and Bada, O.S (2023): Development of Ag-doped on multi-walled carbon nanotubes for the treatment of fish pond effluent. Regional Studies in Marine Science 58 (2023) 102797Regional Studies in Marine Science 58 (2023) 102797. www.elsevier.com.

Almuhanna, A.A, Aldakkan, K.A, Alsalman H.A, Alaskar, Y.A and Alatawi, A.A (2009): Strategic priorities for nanotechnology programme. King Abdulaziz City for Science and Technology, Saudi Arabia.

Asishana, J (2014): FUT Minna records research breakthrough, produces first carbon nano-particles in Nigeria. Daily Newswatch, Wednesday, July 9, 2014, pp.74

Baba, A.I, Mustapha, S, **Abdulkareem, A.S**. Tijani, O.J and Obayomi S.K (2026): Biomass-to-nanomaterial pathways for sustainable environmental remediation: Advances in green synthesis, functional mechanisms, and circular economy prospects. Industrial Crops & Products 243 (2026) 123103 https://doi.org/10.1016/j.indcrop.2026.123103

Baba, A.I, Mustapha, S, Tijani, O.J and **Abdulkareem. A.S** (2026): Green-synthesized magnetite nanoparticles from iron filings via controlled acid leaching for the adsorptive removal of Cr(VI), Pb(II), Cu(II), and organic pollutants from tannery wastewater. Total Environment Engineering 7 (2026) 100080 https://doi.org/10.1016/j.teengi.2026.100080

Bankole M.T, Jimoh O Tijani, Mohammed I.A and **Abdulkareem A.S** (2014): A review of nanotechnology as tool of change in Nigeria. Scientific Research and Essays. Volume9 (8), pp 213-223. www.academicjournals.org/SRE

Bankole, M.T, **Abdulkareem, A.S**, Mohammed, I. A, Ochigbo, S.S, Tijani O. J, Abubakre, O.K and Ross W.D (2019): Selected Heavy Metals Removal from Electroplating Wastewater by Purified and Polyhydroxylbutyrate Functionalized Carbon Nanotubes Adssorbents. Scientific Reports, volume 9 article number 4475. www.nature.com/scientificreports

Bankole, M.T, **Abdulkareem, A.S**, Tijani, O. J, Ochigbo S.S, Afolabi A.S and Roos W.D (2017): Chemical Oxygen Demand Removal from Electroplating Wastewater by Purified and Polymer Functionalized Carbon Nanotubes Adsorbents (2017). Journal of Water Resources and Industry, Volume 18, pp 33-50. www.elsevier.com

Batta, H, Ashong, C and Obot, C (2014): Science, Nano-Science and Nano-Technology Content on Nigeria's Elite and Popular Press: Focus on

Framing and Socio-political Involvement. New Media and Mass Communication, 31 pp 9-19

Bhattacharjee, C.R, Nath, A, Purkayastha, D.D, Mukherjee, B, Sharon, M and Sharon, M (2011): Synthesis and Characterisation of Carbon Nanotubes Using a Natural Precursor: Turpentine Oil. Science Journal Ubon Ratchathani University, 2(1), 36-42.

Dutta, J (2007): Nanotechnology: Overview and applications, power point presentation. Asian Institute of Technology, Thailand.

Egbosiuba, T, C, **Abdulkareem**, A.S, Kovo, A.S, Afolabi, E.A, Tijani, O.J, Bankole, M.T, Bo, S and Wiets Daniel Ross, W.D (2021): Adsorption of Cr (VI, Ni (II), Fe (II) and Cd (II) ions by KIAgNPs decorated MWCNTs in a batch and fixed bed process. Scientific Reports, www.nature.com/scientificreports

Egbosiuba, T.C and **Abdulkareem**, **A.S** (2021): Highly Efficient As-Synthesized Multi-Walled Carbon Nanotubes for Copper (II) and Zinc (II) ion Adsorption in a Batch and Fixed-Bed Process. Journal of Materials Research and Technology 2021: 15: pp 2848-2872. www.elsevier.com

Gabriel, A.A (2014): Nigeria can create wealth through nanotechnology application. News Agency of Nigeria –NAN, December 10, 2014, Accessed July 15, 2015.

Hamlet, C.A.E (2008): Utilization of nanostructured surfaces for sensing applications and the use of nonentities for the fabrication of new materials. PhD Thesis, The University of Birmingham

Ibrahim, M, Agboola, J.B, **Abdulkareem**, **A. S**, Adedipe, O and Tijani, O.J (2021): Effects of elevated temperature on the corrosion resistance of silver–cobalt oxide–titanium dioxide ($Ag/Co_3O_4/TiO_2$) nanocomposites coating on AISI 1020. Scientific Reports (2021) 11:10921 www.nature.com/scientificreports

Idibie, C. A, **Abdulkareem, A. S,** Pienaar, H.C.vZ, Iyuke, S.E and Van Dyk. L (2010): Sulphonation of Polystyrene-Butadiene Rubber with Chlorosulphonic Acid for Proton Exchange Membrane: Kinetic Study. Journal of Applied Polymer Science, Vol. 116, Pp 3473-3479. http://onlinelibrary.wiley.com

Ismaila, B.J, Mustapha, S, Tijani, O.J, **Abdulkareem, A.S**, Olasupo, O.A and Shaba E, Y (2025): Exploring ZnO and CeO_2 nanoparticle films for sustainable food packaging applications. Food and Humanity 5 (2025) 100712, www.editorialmanager.com/foohum/journal_overview.html

Kariim I, **Abdulkareem A.S,** Abubakre O.K, Abdulkareem A, Ibrahim K.A and Afolabi A.S (2018): Application of ϒ-alumina as catalyst support for synthesis of CNTs in a CVD reactor. Journal of Advanced Natural Science: Nanoscience and Nanotechnology, Volume 9, pp 1-7. www.iopscience.iop.org

Medupin, O.R, Abubakre, O.K, **Abdulkareem**, **A.S**, Muriana, A.R and Asipita A,S (2019): Carbon Nanotube Reinforced Natural Rubber Nanocomposite for Anthropomorphic Prosthetic Foot Purpose. Scientific Reports, volume 9 article number 9:20146. www.nature.com/scientificreports

Mudi, K.Y, **Abdulkareem**, **A.S**, Azeez, O.S, Kovo, A.S, Tijani O.J and Eterigho, J.E (2019): Optimization of bi-metallic (Fe-Co) catalyst on kaolin support for carbon nanofiber growth growth in a CVD reactor. Journal of Carbon Letters, http://link.springer.com/journal

Mudi, K.Y, **Abdulkareem**, **A.S**, Kovo, A.S, Azeez, O.S, Tijani O.J and Eterigho, J,E (2020): Development of Carbon Nanofibers/Pt Nanocomposites for Fuel Cell Application. Arabian Journal for Science and Engineering. http://link.springer.com/journal

Mustapha, S, Tijani, O.J, Ndamitso, M.M, **Abdulkareem**, **A.S**, Shuaib, Amigun, A.T and Abubakar.L, H (2021): Facile synthesis and characterization of TiO_2 nanoparticles: X‑ray peak profile analysis using Williamson–Hall and Debye–Scherrer. Journal of Internation Nano Letters, http://link.springer.com/journal.

Odigure, J.O and **Abdulkareem, A.S** (2001). Modelling of Pollutant's migration from gas flaring: A case study of Niger – Delta area of Nigeria. Association for the advancement of Modelling and simulation in enterprises, Lyon France. Volume 62 No 3 Pp 57 – 68 (ISSN: 0761 – 2524). www.amse-modeling.org

Shitu K.O, Bankole M.T, **Abdulkareem A.S**, Abubakre O.K and Ubaka A.U (2017): Application of Gold Nanoparticles for Improved Drug

Efficiency. Journal of Advanced Natural Science: Nanoscience and Nanotechnology, Volume 8, pp 1-8.
www.iopscience.iop.org/issue/2043-6262/8/1

Suleiman, B, **Abdulkareem**, **A.S**, Musa, U, Mohammed, A.I, Olutoye A.M and Abdullahi I.Y (2016): Thermo-Economic Analysis of Proton Exchange Membrane Fuel Cell Fuelled With Ethanol and Methane. Energy Conversion and Management, Volume 117, pp 228-240. www.elsevier.com

Tijani, J.O, **Abdulkareem**, **A.S**, Mustapha, S, Ndamitso, M.M, Bada, S.O and Sagadevan, S (2024): Polyethyleneglycol-polyhydroxylbutyrate functionalized carbon nanotubes for industrial electroplating wastewater treatment. Journal of Separation and Purification Technology 332 (2024) 125736. www.elsevier.com

Tobin, L. and Dingwall, K. (2010), Nanoscience and Nanotechnology: Nigeria, In R. Newton (Ed.), *Second Annual Report on Nanoscience and Nanotechnology in Africa,* Institute of Nanotechnology. Downloaded on 22 November, 2013 at www.iepc.Nanonet.org

ISSN 2550 - 7087
2550 7087