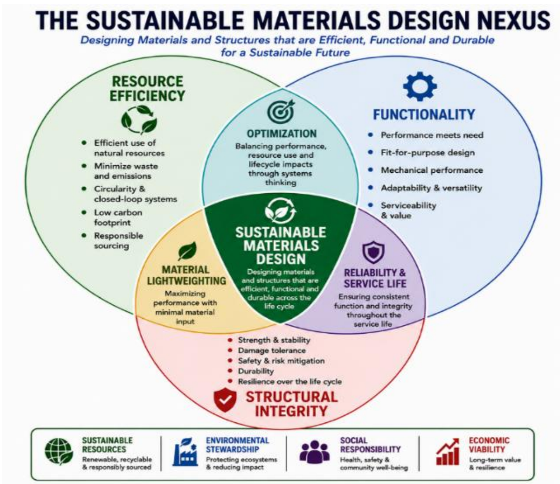
THE FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

SUSTAINABLE MATERIALS DESIGN: PRESCRIPTION FOR OPTIMIZING RESOURCE EFFICIENCY, FUNCTIONALITY, AND STRUCTURAL INTEGRITY

INAUGURAL LECTURE (SERIES 206)



Delivered by

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Tuesday, 8th September, 2026

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Distinguished ladies and gentlemen
Great FUTARIANS!

PREAMBLE

It is with a deep sense of gratitude and appreciation to God, my Maker, Provider, and Protector, the I am that I am, my Lord who anything greater than, cannot be conceived, that I stand before this distinguished audience to deliver this inaugural lecture. An inaugural lecture is an academic ceremony that provides a platform for a Professor to communicate to the wider public, his or her contributions to knowledge in a field, and to explain how these ideas impact on society. Today's lecture is titled 'Sustainable Materials Design: Prescription for optimizing Resource Efficiency, Functionality, and Structural Integrity'. This is the 206th Inaugural Lecture of our great university; it is the fourth from the School of Infrastructure, Mineral and Manufacturing Engineering, the fifth from the Department of Metallurgical and Materials Engineering, and within my department, the first from the Mechanical and Structural Materials Engineering division. It follows after the highly enlightening inaugural lectures of the founding fathers of my department: Prof. O. T. Adepoju (of blessed memory), the pioneer Dean of the defunct School of Engineering and Engineering Technology, Prof. J. O. Borode, Prof. B. O. Adewuyi, and Prof. John Ade Ajayi (of blessed memory).

1. INTRODUCTION

1.1 My Journey into Engineering and Academia

Vice-Chancellor, Ma, my sojourn into the field of Metallurgical and Materials Engineering was guided by divine providence. In the early 1990s, the domestic manufacturing, industrial, and oil and gas sectors were booming, offering attractive career trajectories. Consequently, engineering disciplines such as Mechanical, Chemical, and Petroleum Engineering received the highest subscription from aspiring university candidates. I originally applied through the Joint Admissions and Matriculation Board (JAMB) to study Chemical Engineering at the Federal University of Technology, Owerri (FUTO), but was ultimately admitted into Metallurgical and Materials Engineering through the supplementary admission process. At the time, I possessed little insight into the discipline beyond the basic study and application of metals. My profound appreciation for the field was sparked during my second year upon sitting for the *Introduction to Materials Science* course. This gateway course revealed how the discipline applies foundational scientific and engineering principles to matter derivatives—encompassing metals, polymers, ceramics, wood, and composites—to develop high-performance materials for a wide range of applications. Inspired by the curriculum and the academic brilliance of my Head of Department and subsequent undergraduate project supervisor, Dr. U. H. Udomon, I resolved to give the programme my absolute best.

Following my graduation in 1998, employment opportunities in core engineering could no longer keep pace with the growing number of engineering graduates. More disturbing were the accounts from peers regarding the severe operational and economic decay paralyzing the nation's two flagship metallurgical establishments—the Ajaokuta Steel Company and the Delta Steel Company, Aladja—which conventionally should have been our premier employment destinations. During this industrial imbalance, the rapidly expanding banking and finance sector began aggressively recruiting top engineering and science graduates with promises of attractive remuneration and rapid career advancement. Like many of my contemporaries, I contemplated a career shift into the financial sector, specifically targeting corporate auditing with the intention of pursuing professional certification.

However, this brief consideration of a career in the management sciences was ultimately redirected by three transformative and interlocking events. The first was the counsel from a manager of a multinational auditing firm while I awaited deployment for the National Youth Service Corps (NYSC). She counselled me not to consider abandoning engineering and encouraged me to pursue postgraduate education as a pathway to long-term professional relevance. The second was my NYSC deployment to the Federal University of Technology, Akure (FUTA). Following an interview with the then Head of Department, Prof. John Ade Ajayi (of blessed memory), I assumed substantial teaching and research responsibilities in the department which had only five lecturers at that time. Teaching multiple courses and working closely with senior students, coupled with the encouraging feedback I received, rekindled my interest in academia. My performance subsequently contributed to the department's recommendation of me for appointment as a Graduate Assistant, leading to my enrolment for a Master's degree in 2000. The third, and perhaps most consequential, was my mentorship under Prof. Celestine Monde Kamma (of blessed memory). As my M.Eng. and PhD supervisor, his fatherly guidance, exemplary scholarship, and commitment to mentorship profoundly shaped my academic and research trajectory. Under his influence, what had begun as an emerging interest in academic life became a firm commitment to scholarship, research, and the pursuit of academic excellence.

Through hard work and academic dedication, I rose steadily through the ranks, attaining the pinnacle of the academic ladder as a full Professor in 2017, seventeen years after my initial appointment in the year 2000. Today, twenty-six years into this rewarding journey, I give Almighty God all the glory for the milestones I have been enabled to accomplish within this noble profession.

2. MATERIALS

2.1 Materials and Their Role in Engineering

Materials are physical substances or combinations of substances (derived from matter) from which objects, components, structures, machines, and technological systems are made. In this sense, materials provide the physical foundation upon which engineering innovation is built, translating human ideas into functional products and structures (Banerjee and Williams, 2015).

Engineering materials have traditionally been grouped into three foundational classes: metals, ceramics, and polymers. Metals generally combine strength, ductility, toughness, and thermal and electrical conductivity; ceramics offer high hardness, thermal stability, and chemical resistance, although often with limited toughness; while polymers provide low density, flexibility, toughness, and thermal and electrical insulation (Galsin, 2019). These contrasting characteristics make each class suitable for particular applications, but also expose inherent limitations when increasingly demanding applications require several properties simultaneously. Consequently, modern engineering has moved beyond conventional monolithic materials toward composites, biomaterials, nanomaterials, smart materials, and other advanced material systems designed to overcome conventional property limitations and provide tailored combinations of functionality (SAPEA, 2026).

2.2 Engineering Materials and Load-Bearing Systems

A particularly important category of engineering materials is load-bearing materials. These are materials used in components and structures required to carry and safely transmit mechanical loads throughout their intended service life, while maintaining adequate strength, toughness, durability, and structural integrity (Callister and Rethwisch, 2018; Ashby, 2017). Such loads may arise from tension, compression, bending, shear, torsion, impact, vibration, thermal effects, or combinations of these actions. The performance of load-bearing materials therefore extends beyond simply possessing high strength. They must resist unacceptable deformation, fracture, fatigue, wear, corrosion, creep, and other forms of damage that can compromise structural safety and serviceability (ASM International, 1996). Their behaviour is consequently governed by the interaction among material composition, microstructure, processing history, mechanical loading, and service environment (Callister and Rethwisch, 2018).

Materials design provides the systematic framework for controlling these factors to develop or optimize materials for demanding performance requirements. For load-bearing applications, however, materials design cannot focus on a single property. It must reconcile three fundamental and sometimes competing requirements: resource efficiency, functionality, and structural integrity.

2.3 The Three Pillars of Materials Design

Resource efficiency concerns the responsible use of materials, energy, and other resources throughout the material life cycle. It seeks to reduce dependence on virgin resources, minimize waste and energy consumption, and promote the recovery, reuse, recycling, and incorporation of renewable and waste-derived resources within circular production pathways (Rada, 2023).

Functionality refers to the ability of a material or material system to effectively fulfil its intended operational requirements. Modern engineering increasingly demands multifunctional performance rather than reliance on a single property such as strength. Materials may therefore be required to combine strength, lightweighting, damping, wear resistance, thermal stability, and corrosion resistance, or other functional attributes (Ferreira et al., 2016).

Structural integrity is the ability of a material, component, or structure to withstand its intended service conditions without unacceptable deformation, damage, cracking, or failure throughout its design life. Modern structural-integrity assessment extends beyond bulk strength to consider fracture, fatigue, creep, corrosion, wear, vibration, impact, and other environmental and operational threats that may compromise safety, reliability, and serviceability (Lin et al., 2025; Ferri et al., 2023).

These three requirements form what I describe as the **Materials Design Trilemma**. The central challenge is to achieve resource efficiency and functionality without compromising structural integrity. In high-consequence applications, structural safety remains non-negotiable; consequently, a material cannot be considered truly sustainable if its environmental or economic advantages are achieved at the expense of durability and safe service performance.

2.4 The Sustainability Challenge

This challenge has become increasingly important because conventional materials production remains heavily dependent on virgin resources and energy-intensive processing. At the same time, manufacturing generates substantial industrial waste, while agricultural activities produce large quantities of potentially valuable residues. Circular materials therefore offer an important opportunity to reduce resource consumption and environmental burden by converting scraps, agro-industrial wastes, and other secondary resources into useful engineering materials (UNEP & IRP, 2024). However, sustainability cannot be judged solely by the origin of the feedstock. Waste-derived materials may exhibit variability in composition, impurities, inconsistent supply, and uncertain long-term performance (Bodunrin et al., 2015). Inadequate characterization and qualification can also limit industrial confidence and large-scale implementation.

The critical engineering question is therefore not simply whether waste can be converted into materials, but whether such materials can deliver competitive functionality, durability, and structural reliability while achieving meaningful resource efficiency throughout their service life (Callister & Rethwisch, 2018). Their successful deployment requires rigorous characterization, experimental validation, predictive assessment, and compliance with appropriate engineering standards and codes.

2.5 The Nigerian Materials Challenge

Vice-Chancellor, Ma, the importance of materials to national development is reflected throughout human history, with technological progress closely associated with successive advances in materials technology. Yet many developing economies continue to occupy relatively low-value positions in the global materials supply chain, exporting primary resources while importing refined engineering materials, products, and technologies (UNIDO, 2016; World Bank, 2024).

Nigeria faces corresponding challenges, including dependence on imported engineering products and raw materials, limited local manufacturing capacity, high production costs, inadequate standardization of locally fabricated components, and insufficient adaptation of imported technologies to local conditions (World Bank, 2021; Okejiri, 2000). These limitations can weaken industrial competitiveness and compromise the reliability of engineering systems. At the same time, Nigeria possesses substantial agricultural, industrial, mineral, and human resources capable of supporting indigenous materials development. Agro-industrial wastes, industrial scraps, and other locally available resources can potentially be transformed into value-added engineering materials rather than remaining environmental burdens. The strategic imperative is therefore to move beyond the export of raw resources toward the design, processing, characterization, qualification, and manufacture of value-added materials and engineering products within Nigeria.

2.6 Sustainable Materials Design: The Research Response

This national materials challenge provides the context and motivation for my research response: Sustainable Materials Design. I advance **Sustainable Materials Design** as the overarching focus and guiding paradigm of my research. For load-bearing applications, I define Sustainable Materials Design as a multi-criteria engineering paradigm that integrates circular-economy principles and resource efficiency, with materials chemistry, selection and synthesis, processing and manufacturing technologies, deformation, fracture and damage mechanics, durability, degradation and life extension, structural health monitoring and diagnostics, and life-cycle and multi-criteria assessment to develop and optimize load-bearing material systems. Its objective is to simultaneously optimize **Resource Efficiency, Functionality, and Structural Integrity** (Figure 1).

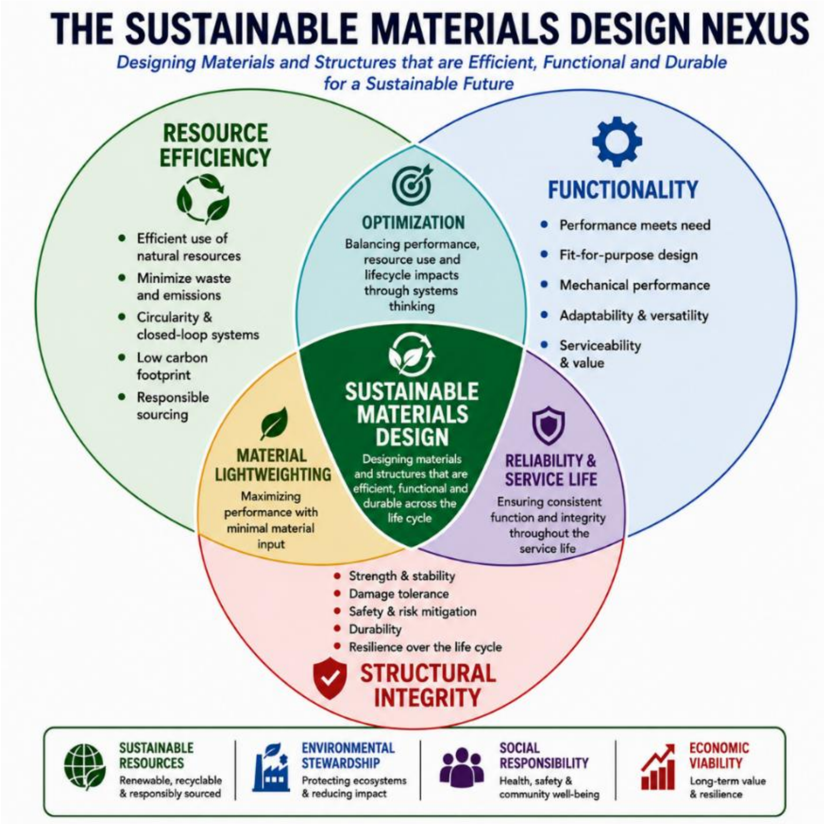

Figure 1. The Sustainable Materials Design Nexus: An integrated framework for efficient, functional, durable and structurally reliable materials.

Within this framework, my 26-year research trajectory has focused on the design, processing, and characterization of sustainable load-bearing materials for demanding mechanical and environmental conditions. By integrating materials design, mechanics, durability, and failure analysis, my research seeks to develop material systems that combine functionality, structural integrity, and resource efficiency. This framework provides the intellectual foundation for the core research themes and contributions presented in this inaugural lecture.

2.6.1 Core Research Themes

My sustainable materials design research is organized around seven interconnected themes: (1) microstructure-engineered sustainable alloys; (2) waste-to-value load-bearing materials; (3) green-engineered structural materials; (4) fracture, degradation, and failure analysis; (5) hard and high-temperature materials; (6) mitigation of structural integrity threats; and (7) locally adaptable designs and enabling technologies.

3. MY CONTRIBUTIONS

3.1 Structural Metallurgy: Sustainable Steel Design

3.1.1 Dual-Phase Steels: Microstructure Engineering and Performance Optimization of Local Grade Steels

A growing demand exists for structural steels that combine high strength, toughness, and ductility for applications in automotive, aerospace, marine, construction, and energy systems (Tasan et al., 2015). Dual-phase (DP) steels address this requirement through a composite microstructure consisting of hard martensite islands dispersed within a soft, ductile ferrite matrix. Their performance depends critically on controlling the ferrite–martensite morphology and volume fractions through appropriate deformation processing and intercritical heat treatment (Kalhor et al., 2020).

Advanced DP steels are commonly produced using alloying additions such as chromium, nickel, niobium, molybdenum, vanadium, and tantalum. However, these specialized grades are not widely processed in Nigeria, where dependence on imported steel remains substantial (Federal Ministry of Steel Development, 2025). Locally available plain-carbon and low-alloy steels are more accessible, but conventional processing does not readily provide the combination of strength and ductility required for demanding structural applications (Alaneme and Kamma, 2009). This motivated our research into microstructure engineering of locally available steels as a pathway to sustainable import substitution

Our initial studies investigated whether controlled deformation followed by intercritical annealing could transform locally available medium-carbon and low-alloy steels into dual-phase materials with useful mechanical properties. We systematically examined the effects of initial microstructure, cold-deformation level, intercritical annealing temperature, and holding time on recrystallization and phase transformation (Alaneme, 2002, 2005, 2007, 2010; Kamma and Alaneme, 2005; Alaneme and Kamma, 2009, 2010; Alaneme and Okotete, 2019). Four starting conditions were investigated: low-, medium-, and high-temperature tempered martensite and normalized steel, subjected to 20–80% cold deformation and subsequently intercritically annealed between 740 and 790°C before water quenching.

The investigations established that the initial microstructural condition and deformation history critically determine the recrystallization mechanism and, consequently, the quality of the resulting dual-phase structure. Stable starting conditions, particularly high-temperature tempered martensite and normalized structures subjected to approximately 50–70% deformation, produced well-defined ferrite–martensite duplex microstructures through primary recrystallization (Figure 2). In contrast, metastable low- and medium-temperature tempered structures promoted continuous recrystallization, which disrupted the desired phase partitioning (Alaneme, 2010; Alaneme and Kamma, 2010).

Building on these findings, subsequent studies optimized the intercritical treatment and evaluated its influence not only on tensile properties but also on fracture toughness, fatigue resistance, and corrosion behaviour (Alaneme et al., 2010a;

Alaneme and Shado, 2010; Alaneme, 2011a; Alaneme and Chidolue, 2011; Alaneme et al., 2013a; Alaneme and Momoh, 2014; Momoh et al., 2016).

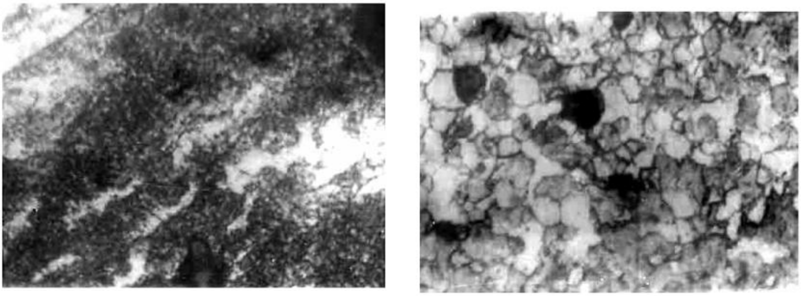

Figure 2: Representative micrograph of (a) as-deformed normalised microstructure, and (b) fully developed dual phase microstructure, intercritical treatment at 760 °C, 60 mins/H_2O.

The results demonstrated that microstructure engineering could substantially improve the property combination of locally available steels without relying on expensive alloy additions. One optimized condition produced a dual-phase steel with a tensile strength comparable to that of fully martensitic steel while increasing elongation from **13.4% to 23.5%—an improvement of 75.4%** (Alaneme and Kamma, 2010). Further optimization identified a dual-phase configuration containing approximately **68% martensite and 32% ferrite**, produced by intercritical annealing at 760°C for 30 minutes. Relative to the normalized condition (Figure 3), this microstructure increased ultimate tensile strength from **754 to 884 MPa**, strain to fracture from **16% to 22%**, fracture toughness from **32.1 to 43.4 MPa√m**, and fatigue endurance limit from **201 to 247 MPa** (Alaneme et al., 2010a; Alaneme, 2011a).

Further investigations confirmed that the ferrite–martensite balance strongly influences both mechanical performance and environmental resistance (Alaneme and Momoh, 2014). An optimum processing window was identified within approximately **38.5–41.6% ferrite and 58.4–62.0% martensite**, producing hardness of 204.7–219.2 HV, ultimate tensile strength of 568.17–646.10 MPa, strain to fracture of 24.88–25.32%, and fracture toughness of 68.75–69.59 MPa√m, together with improved corrosion resistance.

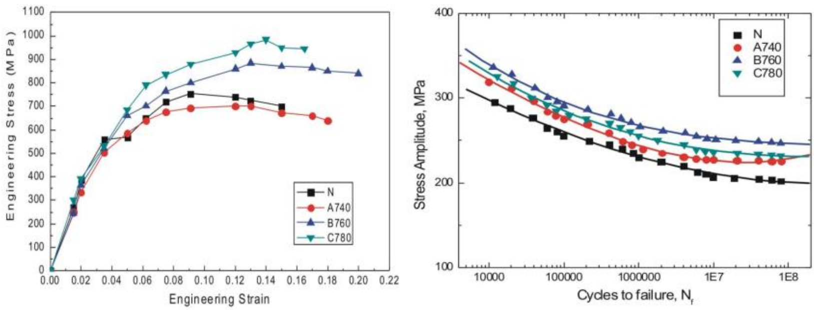

Figure 3. Engineering stress – strain profile and S – N curves for the dual phase steels

Additionally, a two-stage thermomechanical cycling further enhanced the mechanical property range of dual-phase steels. Our investigations revealed that executing a cyclic intercritical routine—consisting of two discrete iterations of cold rolling followed by intercritical annealing at 770°C—stimulated superior structural grain refinement, resulting in significantly improved mechanical and fracture properties (Alaneme et al., 2013a).

The Significance: The optimized steel achieved approximately **585 MPa yield strength, 884 MPa ultimate tensile strength, 22% elongation, and 43.4 MPa√m fracture toughness**, demonstrating a favourable combination of strength, ductility, and damage tolerance. Its performance compares favourably with commercial automotive DP grades (Appendix – Table 1), demonstrating that locally available steels can be microstructure-engineered into higher-performance structural materials. This provides a pathway for indigenous production of critical automotive and structural components, reducing dependence on imported high-performance steels.

3.1.2 Super 304H Austenitic Stainless Steels – Fracture Mechanics, Fatigue, and Micromechanical Damage Tracking

High-temperature components such as pressure vessels, heat exchangers, industrial boilers, and reactor systems operating at approximately 500°C and 870°C require materials with exceptional thermal stability, creep resistance, and corrosion resistance. Conventional solutions rely heavily on expensive alloy steels and nickel-based superalloys containing costly alloying additions such as molybdenum, vanadium, tungsten, tantalum, and niobium (Sen et al., 2011; Alaneme et al., 2013b). Super 304H, an austenitic stainless steel based on Fe–18Cr–9Ni–0.4Nb–3Cu, offers a more economical alternative by combining high-temperature strength and creep resistance with good corrosion protection and recyclability (Ji et al., 2017). Its performance is enhanced by solid-solution strengthening and precipitation hardening associated particularly with copper and chromium-rich phases during thermal exposure. The engineered alloy promotes the formation of finely dispersed copper-rich precipitates within the austenitic matrix, which restrict dislocation movement and contribute to sustained high-temperature strength (Ou et al., 2014; Wu et al., 2024).

Our research addressed an important gap in understanding the ambient fracture and fatigue behaviour of thermomechanically processed Super 304H steels. Alaneme et al. (2010b) systematically investigated alloys containing **0, 1, 3, and 5 wt.% Cu**. Increasing copper content produced only modest reductions in yield and ultimate tensile strength, while ductility remained essentially unaffected up to 3 wt.% Cu (Figure 4). Most significantly, the **3 wt.% Cu composition** exhibited a fracture toughness of **49.7 MPa√m** and a fatigue threshold of **ΔKth = 8.7**

MPa√m, compared with **45.8 MPa√m** and **8.3 MPa√m**, respectively, for the copper-free alloy.

These results demonstrated that controlled copper addition does not compromise ambient damage tolerance and can enhance resistance to fatigue crack initiation and propagation. Fractographic analysis further showed that fracture occurred predominantly through microvoid coalescence associated with debonding of secondary chromium carbides (Figure 5), while copper remained either in solid solution or as finely dispersed precipitates.

The work therefore established a micromechanical basis for understanding the fracture and fatigue behaviour of Super 304H and provided evidence supporting its suitability as a cost-effective, high-temperature structural material for demanding engineering applications.

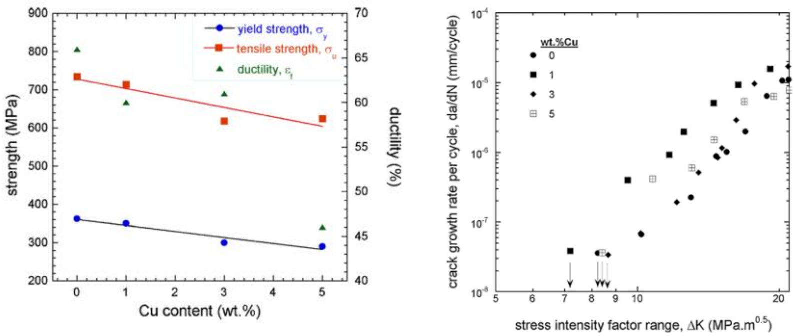

Figure 4. Super 304H austenitic steel (a) representative mechanical properties, and (b) Fatigue crack growth rate curves

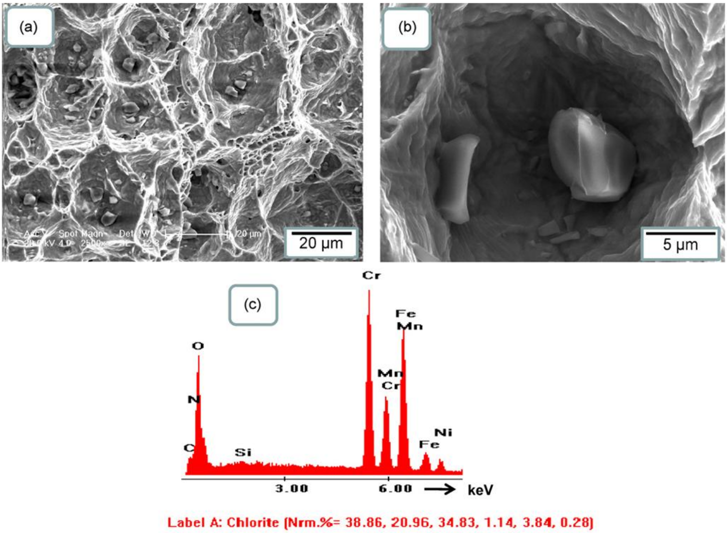

Figure 5. Representative morphology of the fracture in 304H steel (a) low magnification image, obtained from the 3 wt.% Cu containing alloy showing ductile dimple fracture (b) Higher magnification view showing chromium carbide particle in the cavities, (c) EDAX profile obtained from the particle confirming it as $Cr_{23}C_6$.

3.2 Hybrid Reinforced Metal Matrix Composites – Sustainable Synthesis and Performance

Modern engineering increasingly demands materials that combine properties beyond those achievable with conventional monolithic metals, ceramics and polymers. Metal Matrix Composites (MMCs) address this challenge by combining the processing advantages of metallic matrices with the hardness, stiffness, thermal stability, and wear resistance of ceramic reinforcing phases (Bodunrin et al., 2015).

Aluminium is particularly attractive because of its low density, abundance, castability, ductility, and corrosion resistance, although its moderate strength and limited high-temperature stability restrict some applications. Aluminium Matrix Composites (AMCs) provide a means of overcoming these limitations while offering significant weight-saving potential in automotive and other structural components (Ibhadode and Ebhojiaye, 2018; Dash and Chen, 2023).

A major challenge, however, is that conventional ceramic reinforcements such as silicon carbide (SiC) and alumina (Al_2O_3) are expensive and largely imported into Nigeria. Our research therefore pursued two complementary objectives: first, to establish a low-cost local processing capability for MMCs; and second, to replace part of the imported synthetic reinforcement with locally available waste materials.

We first developed and validated a homegrown mechanical stir-casting system integrated with locally available laboratory furnaces (Figure 6). Extensive investigations demonstrated that the system could produce sound AMCs with relatively uniform reinforcement distribution and micro-porosity below 4%, while achieving mechanical, wear, fracture, and corrosion properties comparable with those reported for conventionally manufactured composites (Alaneme, 2011b, 2011c, 2012a, 2013; Alaneme and Bodunrin, 2011, 2013; Alaneme and Aluko, 2012a, 2012b; Bodunrin et al., 2012).

Figure 6. (a) standard automated stir-casting machine, (b) Homegrown stir-casting set-up with innovative mechanical stirring assembly

3.2.1 Agro-Waste as Sustainable Reinforcement

Having established the processing platform, we addressed the more fundamental sustainability challenge of replacing expensive synthetic ceramics with **agricultural-waste-derived reinforcements**. Our studies investigated rice husk ash (RHA), bamboo leaf ash (BLA), groundnut shell ash (GSA), and palm kernel shell ash (PKSA), exploiting their silica- and alumina-rich compositions as partial substitutes for imported SiC and Al_2O_3. This work led to the development of what we termed **Hybrid Reinforced Aluminium Matrix Composites**, combining waste-derived ash with conventional ceramic reinforcement. Our pioneering studies, published from 2013, demonstrated that controlled proportions of agro-waste ash could be incorporated successfully without compromising the fundamental structural integrity of the composite (Alaneme et al., 2013c, 2013d; Alaneme and Olubambi, 2013; Alaneme and Adewale, 2013; Alaneme and Adewuyi, 2013; Alaneme et al., 2014; Alaneme and Sanusi, 2015).

For RHA–Al_2O_3 composites, replacing part of the synthetic reinforcement with RHA maintained low porosity and produced competitive mechanical properties. An optimized composition containing **2 wt.% RHA and 8 wt.% Al_2O_3** demonstrated a particularly favourable combination of specific strength, ductility, and fracture toughness. Subsequent addition of a small quantity of graphite (Figures 7 and 8) further improved strength, fracture toughness, and dry-sliding wear resistance (Alaneme and Sanusi, 2015).

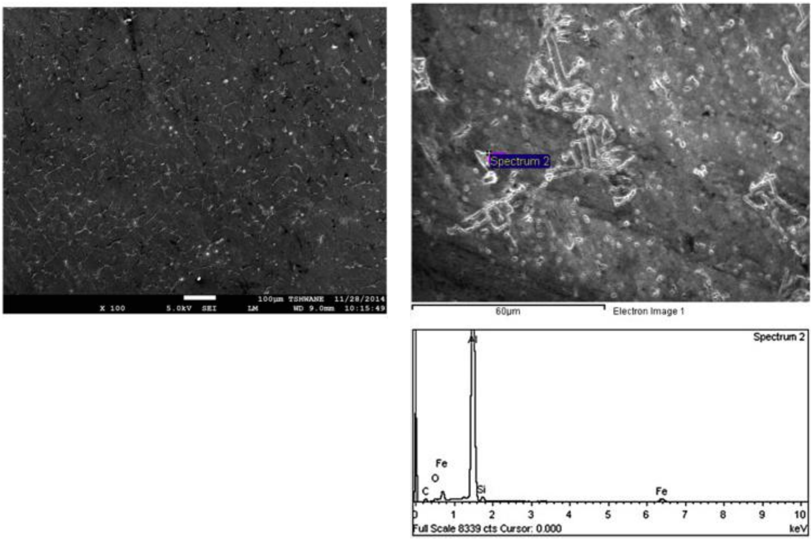

Figure 7. Representative micrographs and EDS profile of of the hybrid reinforced AMCs

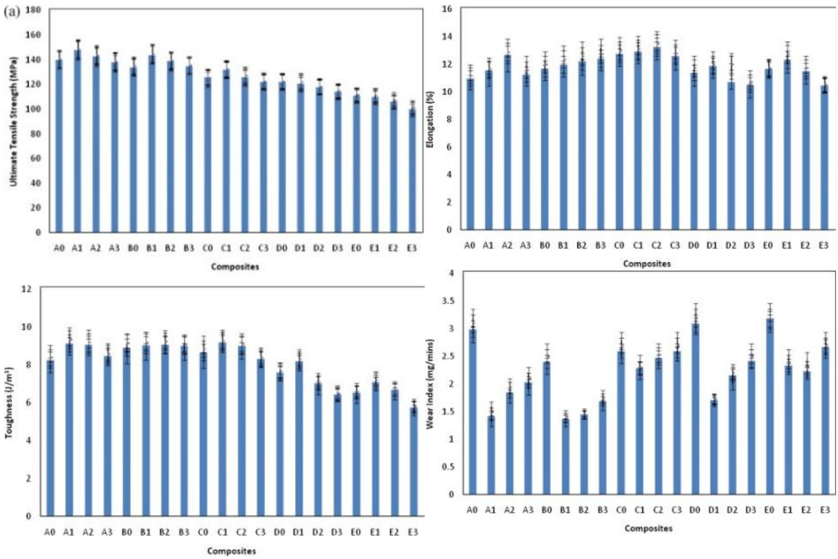

Figure 8. Mechanical properties of the AMCs hybrid reinforced with alumina, RHA, and graphite (code 0, 1, 2, 3, represent 0, 0.5, 1, and 1.5 wt.% graphite)

Our investigations also revealed an important principle of sustainable materials design: increasing waste content does not automatically improve material performance. Excessive RHA replacement produced gradual reductions in strength and corrosion and wear resistance because the irregular ash particles increased matrix–reinforcement interfacial area and created additional sites for localized degradation. Thus, waste utilization must be guided by microstructural optimization rather than simply maximizing waste content (Figures 9 and 10).

Similar investigations using BLA, GSA, and PKSA confirmed that these wastes could function effectively as partial reinforcements. Although some formulations produced modest reductions in strength, appropriately selected hybrid ratios generally improved fracture toughness and, in some cases, corrosion and wear resistance relative to single-reinforced composites (Alaneme et al., 2013d; Alaneme and Adewuyi, 2013; Alaneme et al., 2016; Ikele et al., 2022, 2023).

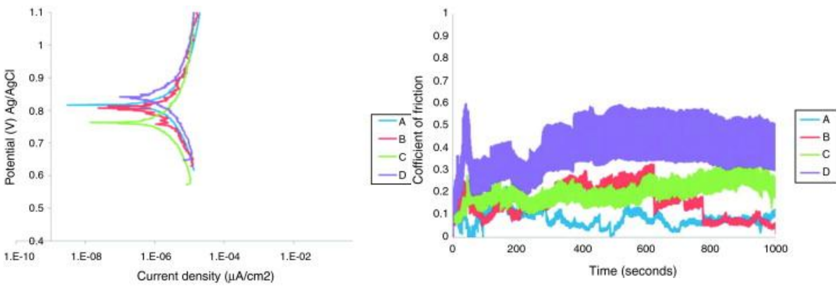

Figure 9. Variations of the (a) Potentiodynamic polarization curves in 3.5% NaCl solution at 25 °C, and (b). Coefficient of friction with time, for the single reinforced Al–Mg–Si/10 wt.% Al_2O_3 and hybrid reinforced Al–Mg–Si/RHA–Al_2O_3 composites.

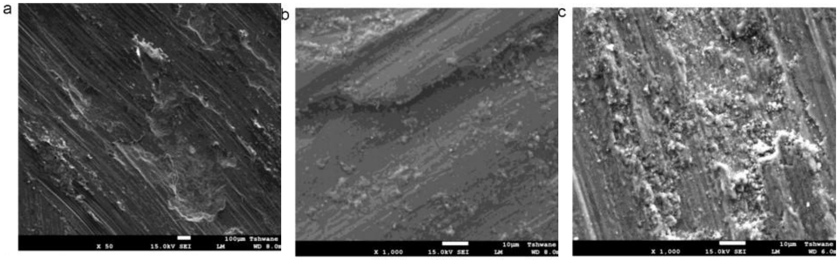

Figure 10. (a) SEM photomicrograph of the worn surface of the single reinforced Al–Mg–Si/10 wt.% Al_2O_3 composite; (b) SEM photomicrograph of the worn surface of the hybrid reinforced Al–Mg–Si/2 wt.% RHA–8 wt.% Al_2O_3 composite; (c) SEM photomicrograph of the worn surface of the hybrid reinforced Al–Mg–Si/4 wt.% RHA–6 wt.% Al_2O_3 composite.

3.2.2 Industrial Waste as Reinforcement

Our sustainable materials strategy was subsequently extended from agricultural wastes to **industrial and manufacturing by-products**. Quarry dust (QD), generated during granite processing, was characterized and incorporated with SiC in aluminium composites (Figures 11 and 12). The resulting materials exhibited competitive tensile and specific strength, while incorporation of QD improved ductility and fracture toughness (Figure 13), demonstrating that an industrial waste stream could be converted into a functional structural reinforcement (Alaneme and Bamike, 2018; Alaneme et al., 2018, 2020).

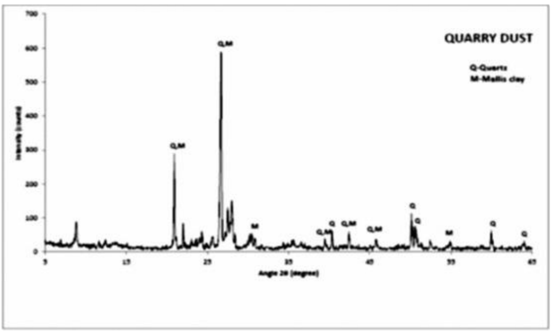

Figure 11. XRD profile of quarry dust

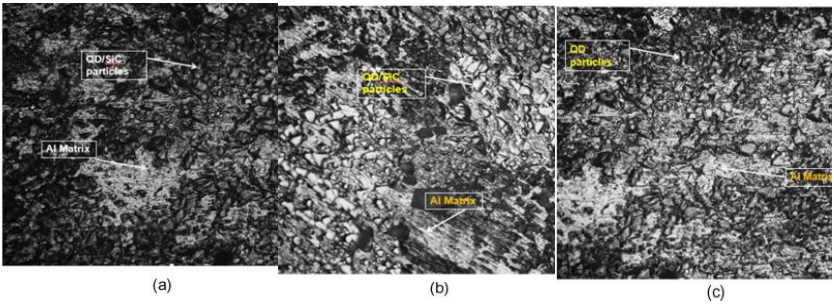

Figure 12. Representative optical micrographs of (a) hybrid SiC and QD (1:1) reinforced, (b) hybrid SiC and QD (1:3) reinforced, and (c) single QD reinforced Al-Mg-Si composites produced.

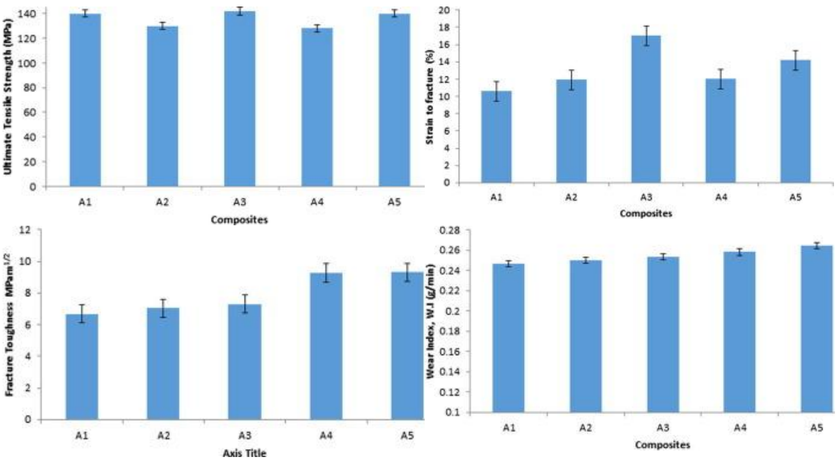

Figure 13. Representative mechanical Properties for the SiC and QD reinforced Al-Mg-Si composites.

An even more distinctive approach involved **recycling steel machining chips as reinforcement**. Rather than treating machining chips solely as waste for remelting, we exploited their high strength, severe prior deformation, and resistance to melting during aluminium processing. Steel-chip-reinforced AMCs exhibited higher hardness, tensile strength, specific strength, and fracture toughness than comparable SiC-reinforced systems

(Figures 14 and 15), with only modest reductions in ductility (Alaneme et al., 2019a).

The addition of graphite produced further tribological benefits, although it also demonstrated the necessary trade-off between different performance requirements. Similarly, steel chips incorporated into copper and Al–Zn matrices produced composites with improved mechanical, wear, and corrosion performance. In Al–Zn composites, the incorporation of **6–8 wt.% recycled machining chips** increased microhardness by approximately **45–75%** and ultimate tensile strength by **9–18%**, while retaining useful fracture toughness and vibration-damping characteristics (Alaneme and Odoni, 2016; Alaneme and Fajemisin, 2018; Alaneme and Aikuola, 2022).

These studies established a broader principle: industrial waste can be deliberately engineered into load-bearing materials when its intrinsic metallurgical characteristics are properly understood and matched to the required function.

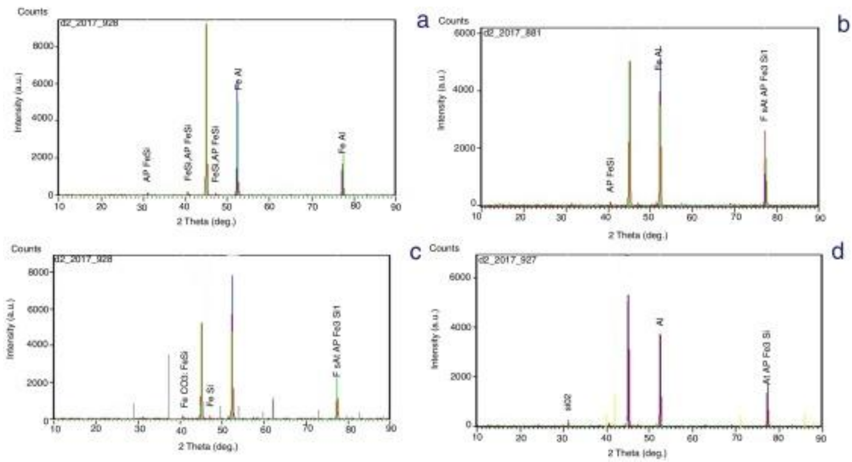

Figure 14. Representative X-ray diffraction patterns of the (a) unreinforced Al-Mg-Si alloy, and the Al-Mg-Si based composites reinforced with (b) 8 wt.% steel particles, (c) 7 wt.% steel and 1 wt.% graphite particles, and (d) 8 wt.% SiC particles.

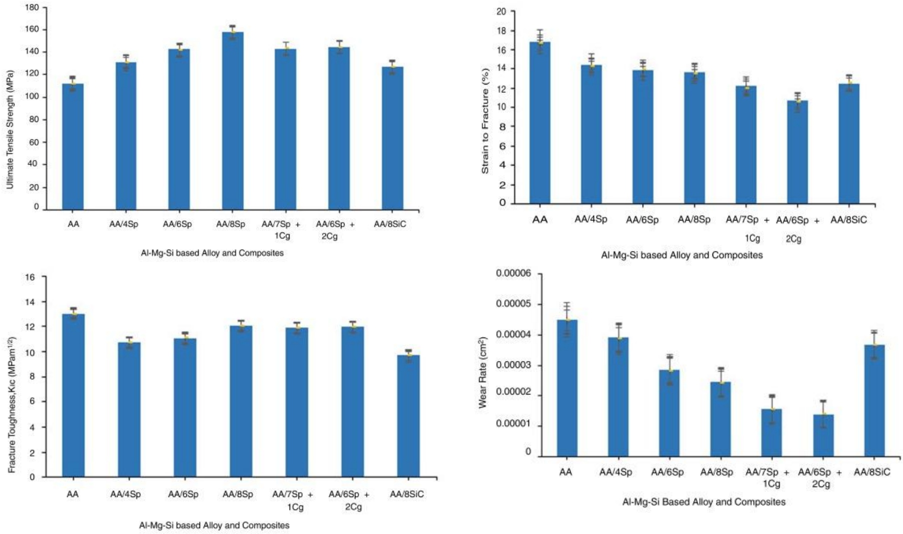

Figure 15. Representative Mechanical properties of the unreinforced Al-Mg-Si alloy, and the Al-Mg-Si based composites reinforced with steel, steel and graphite, and SiC particles.

4.2.3 Homegrown Synthesis of Silicon Carbide

We further pursued the challenge of reducing dependence on imported synthetic reinforcement by developing a **homegrown route for synthesizing silicon carbide from agricultural wastes**. Rice husks, bamboo leaves, and coconut shells were subjected to controlled carbothermal reduction at temperatures between 900°C and 1600°C (Adediran et al., 2018, 2019a, 2019b). Rice husk proved particularly promising, producing approximately **63–74 wt.% crystalline SiC**, substantially exceeding the yields obtained from coconut shells and bamboo leaf ash. X-ray diffraction confirmed the formation of several SiC polytypes, including 3C-SiC and 6H-SiC (Figure 16).

Importantly, the synthesized material was subsequently used as reinforcement in AMCs, whose tensile strength, fracture strain, fracture toughness, and wear resistance fell within the performance range reported for commercially produced SiC (Adediran et al., 2018).

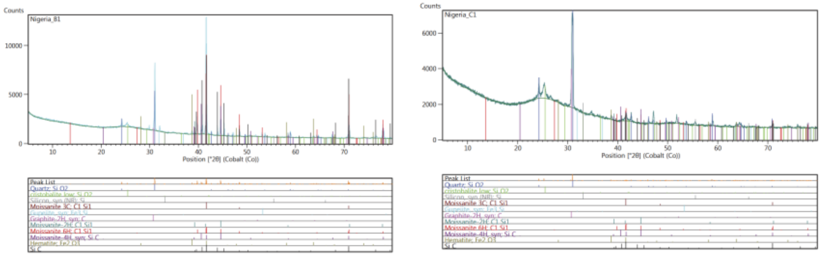

Figure 16. Representative XRD spectrum of polytypes of SiC derivatives from rice husk carbothermal processing.

Significance of the Work

Collectively, these investigations establish a circular pathway for metal matrix composite development in which waste streams are converted into functional reinforcements for engineered structural applications. Our research demonstrates that materials sustainability extends beyond simply replacing conventional materials with waste; it requires deliberate optimization of composition, processing, microstructure, durability, and environmental response. Through this approach, locally abundant materials—including rice husks, bamboo leaves, groundnut shells, palm kernel shells, quarry dust, and steel machining chips—have been transformed from environmental liabilities into value-added resources for advanced load-bearing systems.

3.3 Functional Metallurgy – The Strategic Shift to Copper-Based SMAs

Conventional metallic materials generally undergo irreversible plastic deformation at relatively small strains (as low as 0.2%), whereas shape memory alloys (SMAs) can recover substantial pre-deformation configurations—typically 4–8%—through reversible thermoelastic martensitic transformation. This shape memory effect and superelasticity, together with their high vibration-damping capacity, make SMAs attractive for actuators, biomedical devices, sensors, and passive vibration-control systems (Alaneme and Okotete, 2016; Alaneme et al., 2019b).

Nickel–titanium (NiTi) remains the dominant commercial SMA because of its high recoverable strain, strength, corrosion resistance, and biocompatibility. However, its high material cost and the sophisticated processing infrastructure required for production make it less attractive for large-scale local applications in Nigeria. Our research therefore pursued **copper-based SMAs as lower-cost, locally processable alternatives** to NiTi, with more than a decade of investigations covering Cu–Zn–Al, Cu–Al–Ni, and Cu–Zn–Sn systems (Alaneme et al., 2013e; Alaneme and Okotete, 2016; Alaneme et al., 2017a,b; Alaneme and Umar, 2018; Alaneme et al., 2019b,c; Alaneme et al., 2021; Alaneme et al., 2022a,b; Alaneme et al., 2023; Anaele et al., 2023, 2024, 2026; Alaneme et al., 2025a).

The principal challenges associated with copper-based SMAs include their susceptibility to brittle intergranular fracture, poor workability, phase instability, and precipitation during aging. Our approach was to overcome these limitations through **microalloying and controlled thermal processing**, thereby modifying grain morphology and improving the balance between strength, ductility, fracture resistance, corrosion resistance, and damping. Early investigations demonstrated that a small addition of **0.1 wt.% Fe** to Cu–Zn–Al alloys promoted near-equiaxed grain structures and significantly improved tensile and fracture properties while maintaining good corrosion resistance (Alaneme et al., 2013e). Subsequent Fe–B microalloying produced rounded rather than sharp-edged martensitic grain boundaries (Figure 17), reducing stress concentration and intergranular embrittlement and consequently improving tensile strength, ductility, and fracture toughness (Figure 18) (Alaneme et al., 2017a).

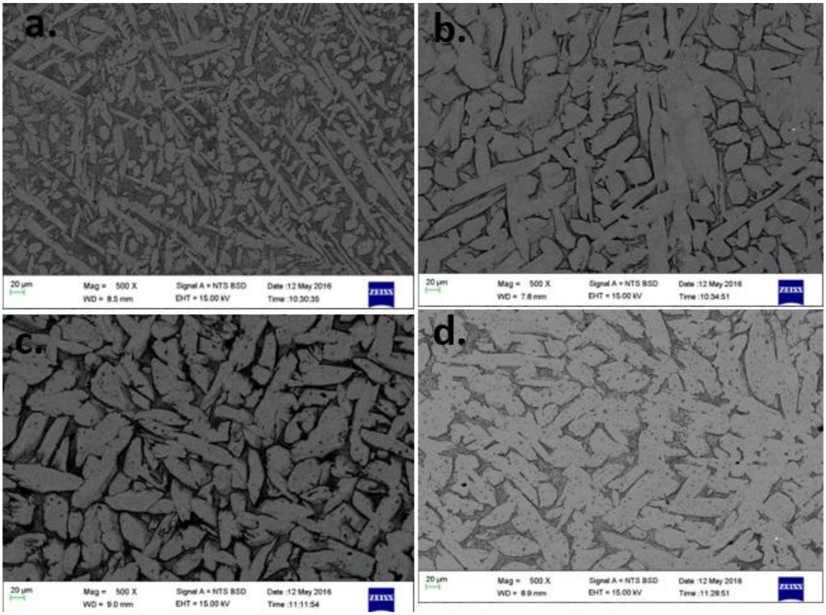

Figure 17: Back scattered SEM images (a) Cu-Zn-Al (b) Cu-Zn-Al-0.05B, (c) Cu-Zn-Al-0.1Fe (b) Cu-Zn-Al-0.05Fe – 0.05B

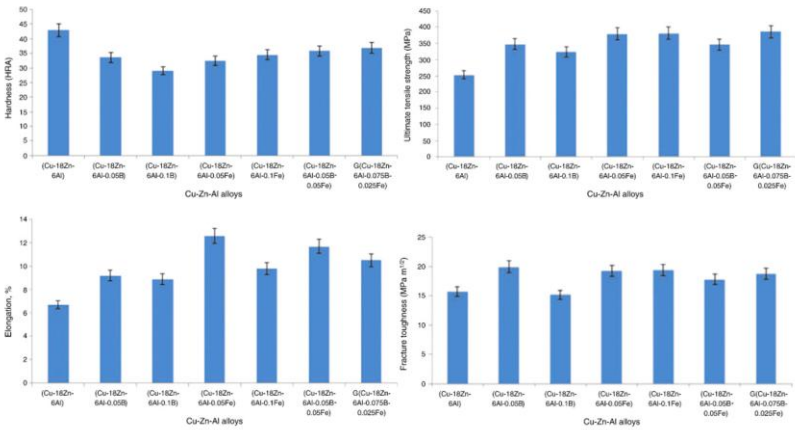

Figure 18. Mechanical properties of the Fe and B modified Cu-Zn-Al alloys

We subsequently established the effectiveness of **nickel microalloying** in modifying Cu–Zn–Al microstructures. Additions of 0.1–0.3 wt.% Ni produced finer, rounded grain morphologies and improved mechanical performance (Figure 19). The 0.2 wt.% Ni alloy provided the most favourable overall response, increasing hardness by 38.4%, tensile strength by 12.16%, and fracture toughness by 28% relative to the unmodified alloy, while also producing the highest internal friction and damping capacity (Alaneme and Umar, 2018). Importantly, the results demonstrated that excessive nickel addition can be counterproductive, establishing a clear microalloying–property optimization window.

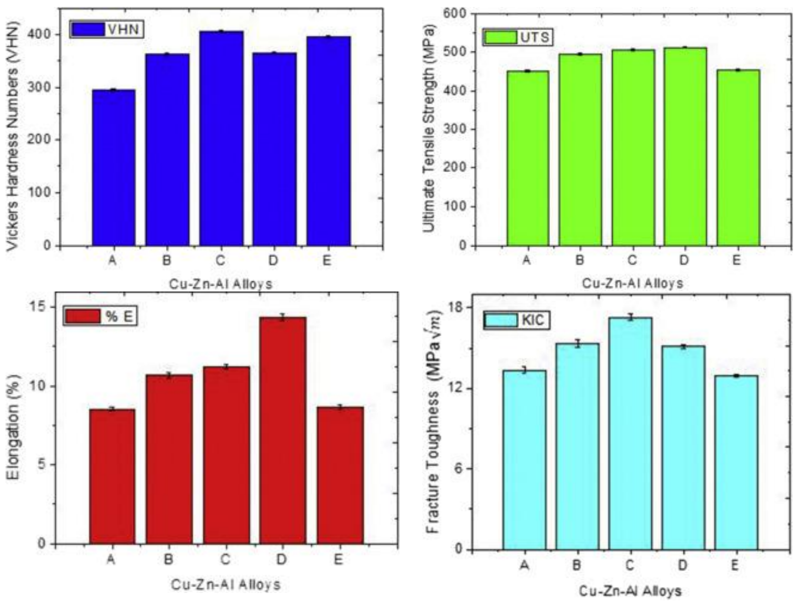

Figure 19. Mechanical properties of the unmodified and Ni modified CuZnAl alloys

Our aging studies further showed that the different alloying strategies produce distinct functional trade-offs. Fe and B additions improved microstructural stability and ductility, whereas Ni promoted strength and fracture toughness but could reduce vibration-damping capacity. This demonstrated that copper-based SMAs must be designed according to the intended balance between **structural integrity and functional performance**, rather than optimized for a single property (Alaneme et al., 2019c).

The research was subsequently extended to **Cu–Zn–Sn SMAs**, providing another potentially low-cost system suitable for local production. Nickel additions produced more uniform grain structures and substantially improved ductility, while the 0.4 wt.% Ni alloy exhibited markedly enhanced vibration-damping capacity compared with the unmodified alloy (Alaneme et al., 2022b).

More recently, we investigated advanced quenching strategies—direct, up, and step quenching—for Cu–Zn–Sn–Fe smart alloys. Step quenching emerged as the most effective treatment, providing the best combination of functional response and environmental resistance (Figure 20). The optimized material exhibited very low corrosion rates in simulated marine conditions (0.025 mm/yr in 3.5 wt.% NaCl), together with high superelastic strain recovery of **91.9–93.41%** under nanoindentation loads of 100–200 mN (Anaele et al., 2023, 2024, 2026).

Collectively, these studies established a design pathway for transforming relatively low-cost copper alloys into functional structural materials through microalloying, grain-boundary engineering, and controlled thermal processing. The work demonstrates that the performance gap between locally accessible Cu-based SMAs and premium NiTi systems can be narrowed through deliberate microstructure–property engineering, creating opportunities for locally manufacturable vibration-control, actuator, sensing, and other smart-material applications.

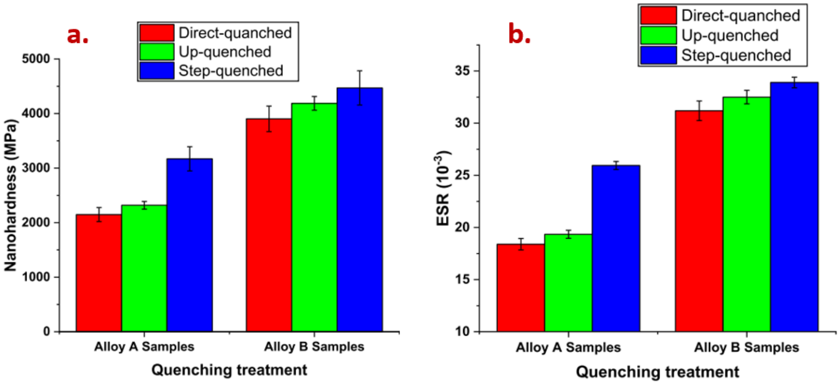

Figure 20. Representative nanomechanical properties (a.) Nanohardness, and (b.) Elastic strain resistance to failure of the CuZnSn SMA samples at indentation load of 100mN.

3.4 Sustainable Biomaterials: Animal Waste as a Source for Orthopaedic Bone Implants and Scaffolds

The need for affordable, locally produced biomedical materials has motivated our research on converting locally available material resources and biological wastes into value-added biomaterials for orthopaedic applications (Alaneme and Edwin-Ezeh, 2022; Alaneme et al., 2024, 2025b; Alaneme and Adeniran, 2025; Alaneme et al., 2026; Osarodion et al., 2026).

Hydroxyapatite (HAp) is particularly attractive for bone implants and scaffolds because of its chemical and crystallographic similarity to the mineral phase of human bone (calcium orthophosphate - $Ca_{10}(PO_4)_6(OH)_2$), which promotes biocompatibility and integration with host tissue. Our work extended the established concept of biowaste-derived HAp to less-explored agricultural wastes, particularly **poultry manure and pig dung**, thereby linking waste valorisation with local resource utilization and biomedical innovation.

Our initial studies investigated the synthesis of HAp from poultry manure through controlled calcination at 750°C, 800°C, and

850°C for 5 hours (Figure 21) (Alaneme et al., 2025b). X-ray diffraction confirmed crystalline HAp as the dominant phase, while increasing calcination temperature improved crystallinity, structural yield, particle uniformity, and Ca/P ratio (Figures 22 and 23). The Ca/P ratio increased from 1.28–1.54 at the lower processing temperatures to an optimum value of **1.71 at 850°C**, approaching the stoichiometric value characteristic of bone-like HAp.

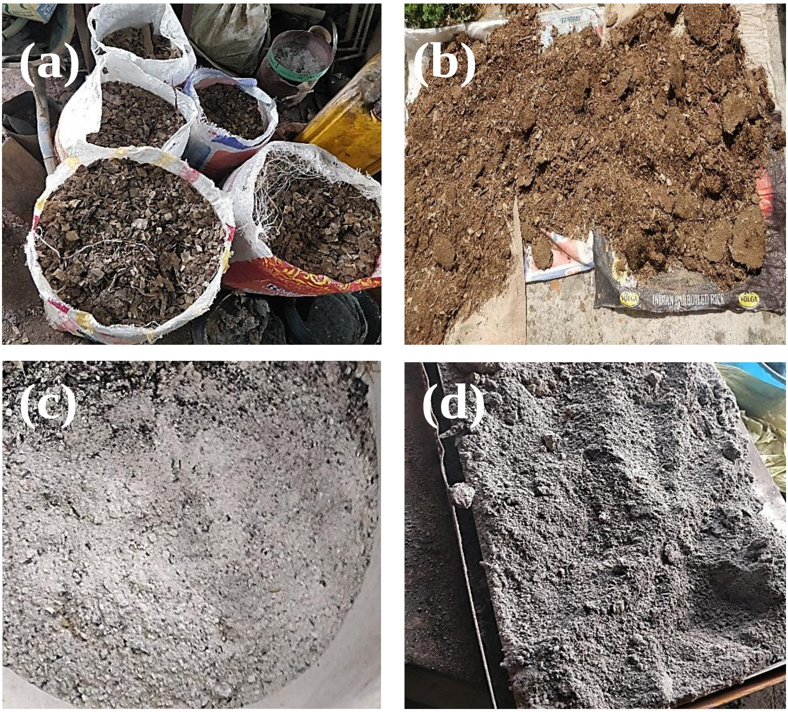

Figure 21. Poultry Manure Processing (a) As-received Poultry Manure, (b) spreading out for air-drying of the Poultry manure, (c) Poultry Manure Ash after air-burning, and (d) Poultry manure after thermal calcining

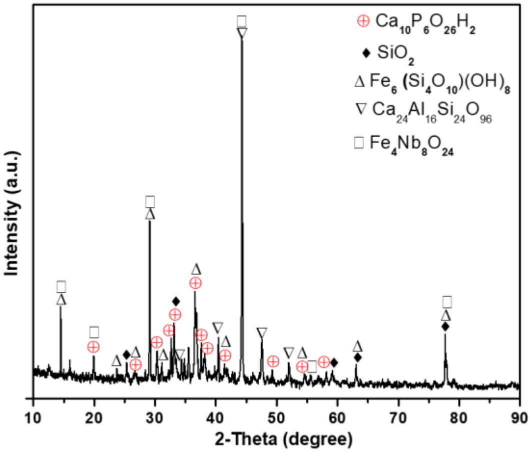

Figure 22. XRD pattern of the phase present in the 750℃ calcined poultry manure

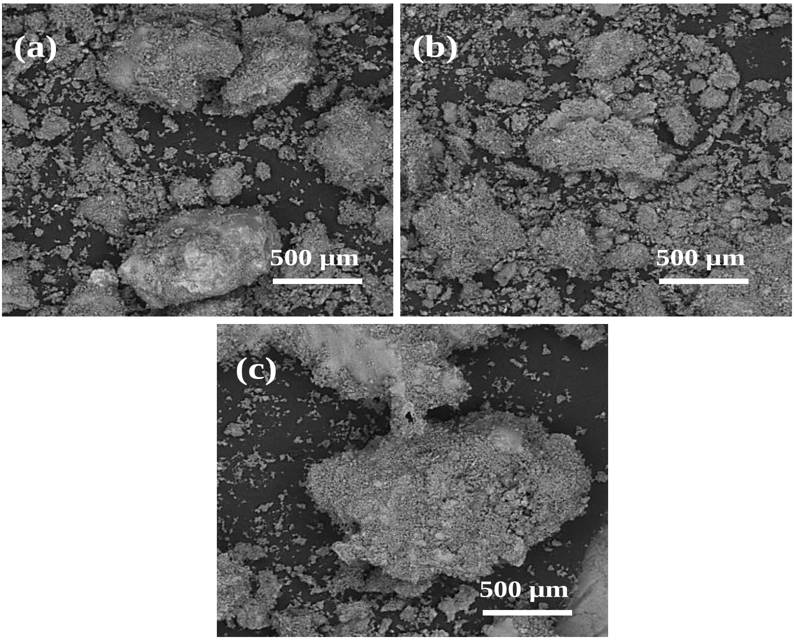

Figure 23. SEM powder morphology of the calcined poultry manure processed at (a) 750℃, (b) 800℃, and (c) 850℃

We subsequently assessed the biological safety of the poultry-manure-derived HAp using *in vitro* antioxidant assays and *in vivo* animal studies (Alaneme et al., 2024). The material exhibited appreciable antioxidant activity, with the 750°C product showing the strongest response. Importantly, animal studies revealed **no adverse hepatic, renal, histopathological, or microbiological effects**, with treated groups maintaining physiological profiles comparable to healthy controls (Figure 24).

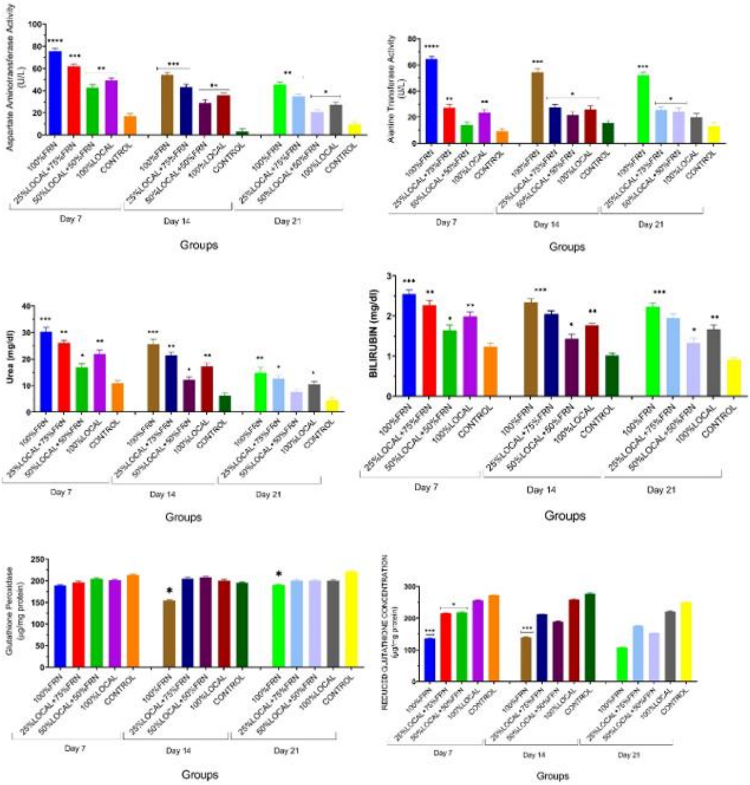

Figure 24: Effects of varied compositions of analytical high grade and thermally calcined poultry manure-derived hydroxyapatite on serum, liver, and kidney biochemical parameters on Days 7, 14 and 21.

These findings provide encouraging pre-clinical evidence for the biosafety of the waste-derived material, although further clinical investigations remain necessary before human application.

We further explored pig manure as an alternative HAp feedstock (Osarodion et al., 2026). Initial calcination at 750°C–850°C produced only 11.3 ± 5% to 14.0 ± 4% crystalline HAp, demonstrating that thermal treatment alone was insufficient to achieve a high HAp yield (Figure 25).

Figure 25. Processing stages of the pig manure (a) Pig manure before air drying (b) Pig manure after air drying for 5 days (c) Pig manure ash after air burning (d) Calcined pig manure

We therefore introduced a post-calcination chemical treatment to improve phase recovery (Figures 26 and 27). This intervention increased the crystalline HAp yield dramatically to **62 ± 5%–72 ± 3%**, demonstrating the effectiveness of combining thermal and chemical processing for upgrading this otherwise low-value waste stream.

Figure 26. Treatment of the calcined Pig manure (a) Calcined pig manure after treatment (b) Impurities separated from the calcined pig manure after treatment

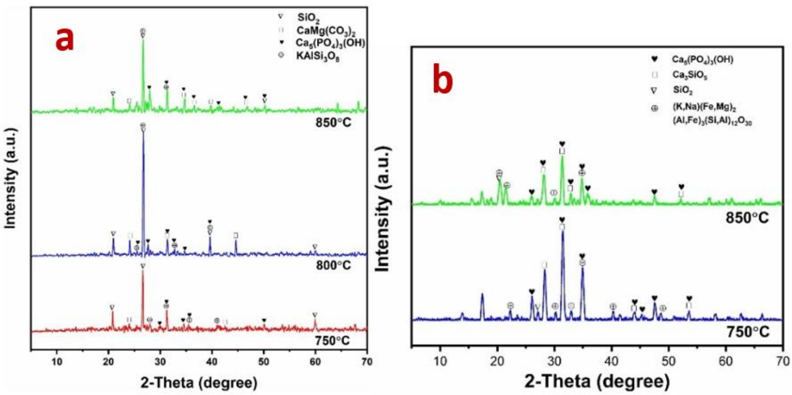

Figure 27. XRD pattern of the (a) untreated pig manure calcined at 750 °C, 800 °C, and 850 °C, and (b) treated pig manure calcined at 750 °C and 850 °C.

The resulting materials exhibited Ca/P ratios characteristic of naturally derived, non-stoichiometric HAp. Raw calcined products recorded ratios of 1.91, 1.81, and 1.52 at 750°C, 800°C, and 850°C, respectively, while chemically treated products recorded 2.36 and 1.77 at 750°C and 850°C. Minor secondary phases, including hatrurite, quartz, and osumilite, were also identified. These results demonstrate that animal wastes can serve as viable feedstocks for producing HAp, provided that processing conditions are carefully optimized to control phase composition and yield.

Collectively, this research establishes a circular pathway for converting problematic animal wastes into potentially valuable orthopaedic biomaterials. It demonstrates the feasibility of integrating waste valorisation, materials processing, phase engineering, and biological evaluation to develop locally sourced alternatives for healthcare applications, while identifying the additional processing and clinical validation required before translation to human use.

3.5 Fracture Mechanics and the Development of an Accessible Structural-Integrity Assessment Approach

In high-consequence structural applications, material selection must provide more than adequate strength; it must ensure functionality, durability, service longevity, and fail-safe performance. Conventional strength-based design compares applied stress with yield or ultimate tensile strength, but does not explicitly account for defects such as pores, inclusions, manufacturing flaws, and microcracks. A component containing a sufficiently severe defect may therefore fail at stresses well below its nominal strength (Wang et al., 2024).

Fracture mechanics addresses this limitation by explicitly considering crack size, geometry, and local stress state. The central question consequently changes from *"How strong is the material?"* to *"Can the material safely tolerate a defect of a given* *size under the prevailing service conditions?"* Fracture toughness therefore provides a critical quantitative measure of structural damage tolerance (ASTM E399, 2024; ASTM E1820, 2022).

International procedures, particularly ASTM E399 and ASTM E1820, provide rigorous approaches for fracture-toughness assessment, with CT and SENB specimens forming established standardized configurations. However, these conventional configurations require specialized equipment, fatigue pre-cracking, relatively large specimens, sophisticated instrumentation, and demanding testing procedures (Alaneme, 2011a). These requirements can present substantial barriers in resource-constrained laboratories.

To address this challenge, Alaneme and co-workers developed and systematically validated the Circumferential Notch Tensile (CNT) approach as a simpler and more accessible method for fracture-toughness assessment (Alaneme, 2011a; Alaneme et al., 2020). The circumferential notch generates a highly constrained and triaxial stress state at the notch root, promoting conditions representative of plane-strain fracture behaviour. Its axisymmetric geometry, smaller specimen requirement, and compatibility with conventional tensile-testing equipment offer important practical advantages over conventional fracture-testing configurations. This development represents a fundamental shift from conventional strength-based assessment toward defect-tolerant structural-integrity evaluation, as illustrated in Figure 28.

In a series of validation studies spanning more than a decade, precisely machined CNT specimens were subjected to quasi-static tensile loading at a controlled true strain rate of $10^{-4}s^{-1}$. Fracture toughness was determined from the measured fracture load and specimen geometry using the validated CNT stress-intensity relationship in Equation (1):

$$K_I = \frac{0.526 \times P \times \sqrt{D}}{d^2} \tag{1}$$

where P is fracture load, D is gauge diameter, and d is notch diameter.

Validity was established by satisfying the required **plane-strain conditions**. Specimens were prepared with a minimum length of 4D, while post-test compliance was assessed using Equation (2):

$$D \geq \left(\frac{K_{IC}}{\sigma_y}\right)^2 \tag{2}$$

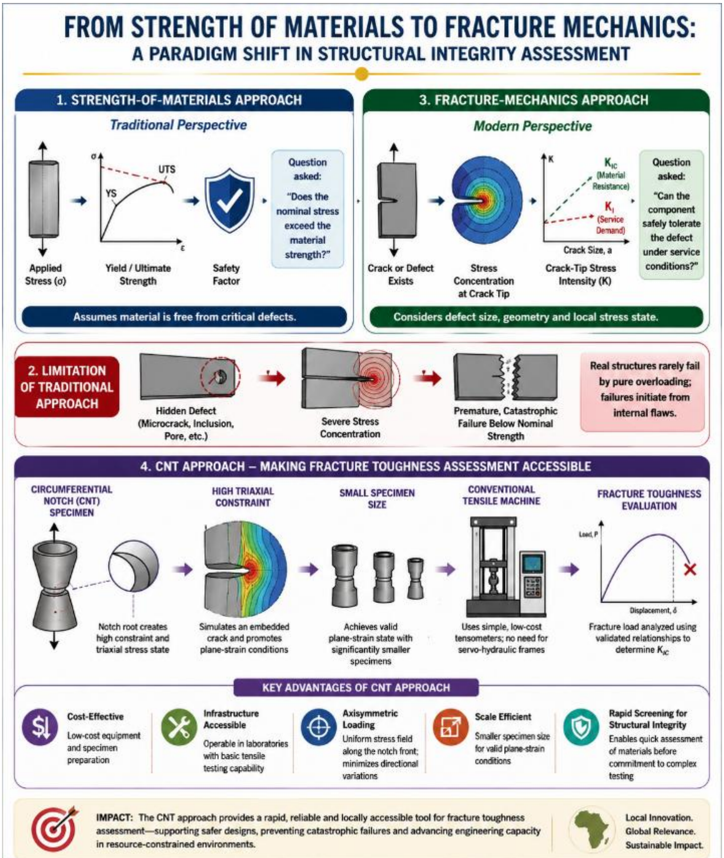

Figure 28. From Strength of Materials to Fracture Mechanics: A Paradigm Shift in Structural Integrity Assessment

The CNT methodology was subsequently evaluated across diverse engineering materials, including high-strength and dual-phase steels, aluminium matrix composites, and copper-based shape-memory alloys. The resulting fracture-toughness measurements showed good agreement with corresponding values obtained using established procedures, with differences generally within 10–15% across the investigated material systems (Appendix – Table 2).

The significance of this work extends beyond an alternative specimen configuration. It demonstrates that locally developed engineering methodologies can reduce the cost and infrastructure barriers associated with advanced structural-integrity assessment. The CNT approach therefore offers a potentially accessible screening route for evaluating fracture resistance before more elaborate standard testing, supporting safer materials selection, indigenous testing capability, and improved structural-integrity assessment in resource-constrained environments.

3.6 Forensic Engineering and Industrial Failure Diagnosis

Vice-Chancellor, Ma, an important contribution of materials engineering to industrial development is the ability to determine why engineering components fail and how such failures can be prevented. Forensic engineering provides a systematic pathway from failure observation to root-cause diagnosis and corrective action. Our research group applied this approach to locally manufactured punching dies and motorcycle driving sprockets, demonstrating how appropriate materials selection, processing and heat treatment can substantially improve indigenous products.

3.6.1 Forensic Diagnosis of Punching Die Failure

Punching dies used for cable-tray production experience repeated impact and cyclic loading and therefore require an appropriate combination of hardness, strength, toughness and resistance to fatigue and chipping (Figures 29 and 30). We investigated premature fracture of locally produced dies by comparing them with imported counterparts using chemical analysis, metallography and microhardness measurements (Alaneme et al., 2009).

Chemical analysis indicated that material composition was not sufficient to explain the inferior performance (Appendix – Table 3). Microstructural examination, however, revealed pronounced deformation features associated with machining, indicating that appropriate post-manufacturing heat treatment had been omitted or inadequately applied (Figure 31). The resulting highly stressed condition reduced toughness and promoted cracking and chipping under repeated impact.

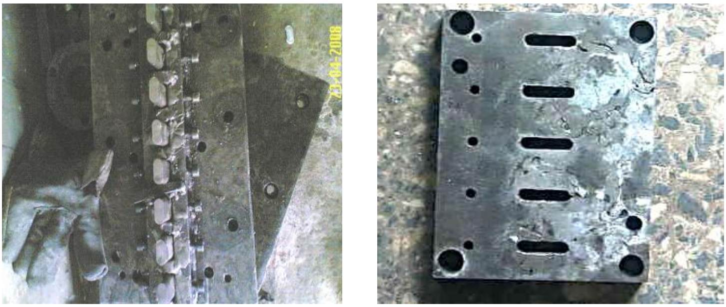

Figure 29. The key component parts of the mould housing (a) upper plate of the punching machine (b) lower plate of the punching machine

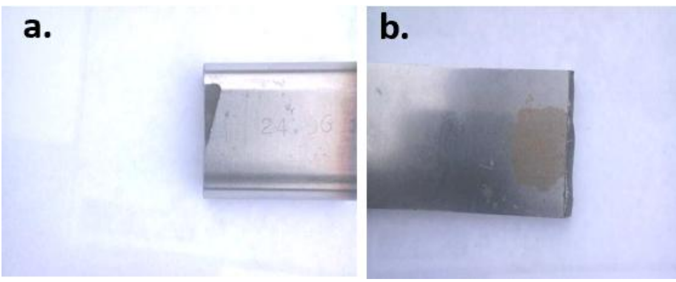

Figure 30. Failed Punch die teeth (a) Imported brand (b) locally processed

A corrective heat-treatment schedule involving austenitizing at 970°C for one hour, followed by normalizing and tempering at 330°C for one hour, substantially improved the microstructural condition of the dies. Their average service life increased from approximately two weeks to four months. Die misalignment and operation beyond the rated machine capacity were also identified as contributing factors.

Forensic lesson: *Material condition + processing + service conditions collectively determine component reliability.*

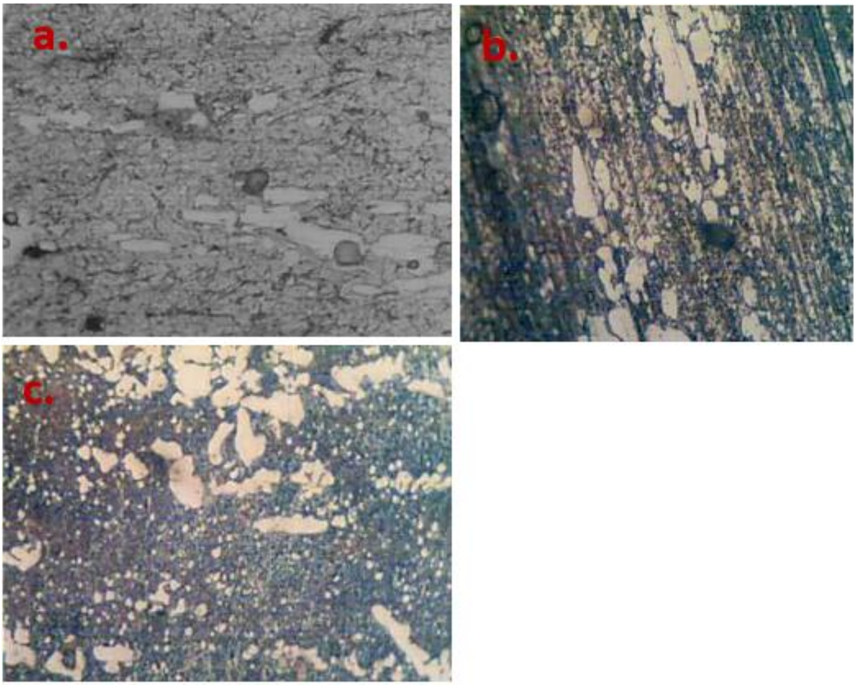

Figure 31. Microstructures of (a) imported punch die, (b) as-received locally produced punch die, (c) locally produced punch die after stress-relief annealing

3.6.2 Forensic Diagnosis and Sustainable Redesign of Motorcycle Sprockets

A similar investigation addressed the rapid wear and short service life of locally manufactured motorcycle driving sprockets (Figure 32) (Alaneme, 2012b). Field assessment, chemical analysis, hardness measurements and metallography revealed that the local sprockets were produced from medium-carbon steel, whereas the imported components used a higher-carbon, manganese-containing steel with greater hardness and wear resistance (Appendix – Table 4). The local sprockets recorded **32.3 HRC**, compared with **45.8 HRC** for the imported components. Rather than relying on expensive alloy steels, we developed a more sustainable solution using locally available low-carbon steel followed by **pack carburizing, quenching and tempering**. This produced a hard, wear-resistant surface while retaining a tougher core capable of absorbing service shocks (Appendix – Table 5). Hardness increased from **23.4 to 44.5 HRC**, approaching that of the imported sprocket (Appendix - Table 6).

Forensic lesson: *Appropriate material + surface engineering = improved wear resistance and service performance.*

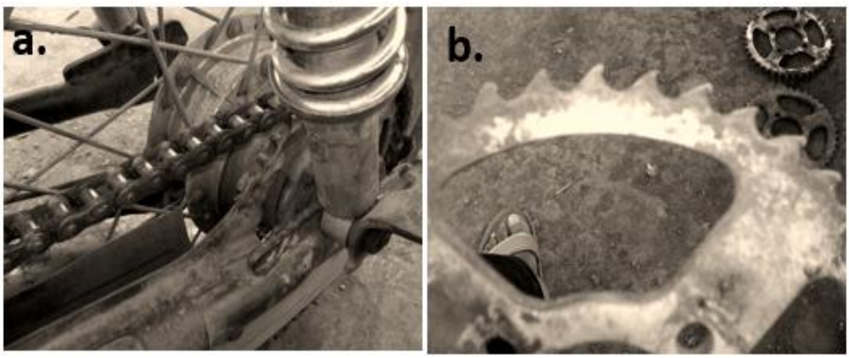

Figure 32. Showing (a) A sprocket linked to the motorcycle chain, and (b) a worn out sprocket.

3.6.3 From Failure Diagnosis to Industrial Learning

These investigations demonstrate that failure must be converted into knowledge for improved design. In the punching-die case, inadequate heat treatment and excessive loading caused premature failure, while in the sprocket case, incorrect material selection was resolved through carburizing and surface engineering. In both instances, accessible interventions substantially improved performance. The broader forensic lesson is that component reliability is governed by the relationships among composition, processing, microstructure, and service conditions. This transforms the cycle—Failure → Evidence → Root Cause → Intervention → Validation—into a powerful mechanism for reduced industrial downtime, enhanced operational safety, and stronger indigenous manufacturing capability.

4. FROM LABORATORY FRONTIERS TO NATIONAL CAPACITY: SCIENTIFIC IMPACT, PEDAGOGICAL ARCHITECTURE, AND LEGACY

4.1 Research Impact, Innovation and Global Legacy

Vice-Chancellor, Ma, the ultimate value of engineering research lies not only in publications, but in its capacity to generate knowledge, develop technologies, build human capacity, and address societal needs. Over twenty-six years of scholarship in sustainable materials design for load-bearing applications, my research has produced more than 230 peer-reviewed publications, including over 163 Scopus-indexed papers, with more than 9,040 citations and a Google Scholar H-index of 47. My work has also been recognized through inclusion among the world's top 2% of scientists for five consecutive years in the Stanford University–Elsevier global rankings.

A defining feature of this scholarship has been the deliberate translation of scientific knowledge into indigenous technological capability, consistent with FUTA's philosophy of *Technology for Self-Reliance*. This has resulted in four national patents covering a controlled-atmosphere heat-treatment furnace, synthesis of crystalline silicon carbide from rice husks, a multifunctional mechanical testing machine, and a gravimetric thermal-analysis machine.

The research programme has also generated pioneering contributions in materials science, including hybrid aluminium matrix composites incorporating agricultural-waste ashes and ceramic reinforcements, the development and application of the Circumferential Notch Tensile (CNT) fracture-testing approach for resource-constrained environments, and pioneering research on copper-based shape-memory alloys. These activities have been supported through competitive national and international funding from organizations including TETFund, the National Research Foundation of South Africa, the Association of Commonwealth Universities, German Academic Exchange Service (DAAD), and the Carnegie Corporation of New York.

Yet, the most enduring measure of this legacy is human capacity. I have supervised and mentored more than 150 B.Eng., 30 M.Eng., and 15 Ph.D. students. Two former doctoral students, Prof. F. O. Aramide and Prof. Mrs. C. M. Ikumapayi, have attained professorial rank, while Associate Professors M. O. Bodunrin and A. A. Adediran have received recognition among the Stanford Top 2% of global scientists. Many other alumni now contribute as academics, engineers and researchers across power, oil and gas, manufacturing, automotive, aerospace, healthcare and related sectors.

4.2 From Research Experience to a New Pedagogical Architecture

Vice-Chancellor, Ma, the second dimension of this legacy is the translation of twenty-six years of research and teaching into a coherent educational framework for **Mechanical and Structural Materials Engineering**. My scholarship has progressively extended beyond the conventional boundaries of metallurgical and materials engineering by integrating **materials science with solid mechanics from mechanical engineering and structural analysis from civil engineering**, alongside sustainability engineering. This integration reflects the reality that structural performance depends not only on the material itself, but also on its mechanical response and interaction with the service environment.

This experience provides the foundation for a three-pillar educational architecture: **Materials Design & Manufacturing; Mechanics of Materials & Environmental Response; and Life Span, Durability & Failure Analysis**. Together, these pillars establish an end-to-end framework linking material creation to mechanical response, environmental interaction, degradation, structural integrity, and failure prevention (Appendix – Table 7).

5. ONGOING RESEARCH INITIATIVES

Our laboratory is currently collaborating with colleagues in the life and medical sciences, civil engineering, and mechanical engineering on four multidisciplinary initiatives aimed at advancing sustainable materials design:

- Bio-Implants: Developing waste-derived hydroxyapatite for bone scaffolds with appropriate Young's modulus, degradation kinetics, osteointegration capability, and biosafety.
- Sustainable Concrete: Upcycling waste tyres and agro-waste pozzolans into lightweight, vibration-absorbing concrete by

optimizing interfacial bonding to balance compressive strength and damping.

- Ballistic Shields: Developing locally sourced, high-performance composites with high energy-absorption capacity and resistance to interlaminar delamination under high-strain-rate ballistic impact.
- Drug Delivery: Engineering sustainable, stimulus-responsive polymer systems with controlled viscoelasticity and density to regulate diffusion and minimize burst release.

6. CONCLUSION

This inaugural lecture demonstrates that sustainable materials design is a practical framework for simultaneously achieving resource efficiency, functionality, durability, and structural integrity. Twenty-six years of research establish four principal lessons for Nigeria's pursuit of technological self-reliance.

First, microstructure engineering can upgrade affordable materials. Microalloying, controlled deformation processing, and tailored heat treatment can significantly improve the strength, toughness, wear resistance, and service life of locally available steels and shape-memory alloys. However, substitution of virgin materials with local scrap must remain evidence-based and guided by verified composition and performance.

Second, waste can become a valuable engineering resource. Agro-industrial wastes can serve as reinforcements for metal matrix composites and as feedstocks for sustainable construction and biomedical materials. Commercial viability must, however, remain central to green engineering, with processing cost, material consistency, and structural reliability considered alongside environmental benefits.

Third, sustainable feedstocks require stabilization and quality control. Our work on animal-waste-derived hydroxyapatite demonstrates the potential for converting problematic biological wastes into value-added biomedical materials through controlled processing and chemical treatment. Nevertheless, biomedical applications demand rigorous biosafety and clinical validation before human use.

Fourth, structural reliability requires comprehensive damage evaluation. Low-cost approaches such as Circumferential Notch Tensile testing can provide valuable preliminary fracture-resistance screening in resource-constrained environments, but should complement rather than replace internationally recognized standards. Materials must ultimately be assessed under realistic combinations of temperature, corrosion, wear, fatigue, vibration, impact, and other service conditions.

The central message is therefore simple: Sustainability must never be pursued at the expense of performance, safety, or reliability.

7. RECOMMENDATIONS

To translate these research outcomes into national productivity and technological self-reliance, I propose four strategic interventions.

7.1 Research Funding and National Laboratory Infrastructure

Government should increase dedicated funding for proof-of-concept, pilot-scale and translational engineering research, enabling universities to move validated discoveries beyond the laboratory. Centralized, well-equipped materials characterization and testing facilities should also be established across the geopolitical zones to reduce dependence on overseas testing and retain both expertise and financial resources within Nigeria.

7.2 Local Content, Standards and Certification

National policies should provide stronger incentives for industries to adopt validated Nigerian-made materials and technologies through appropriate tax incentives and local-content provisions. SON, NSE and COREN should collaborate on national performance standards and certification frameworks for sustainable structural materials, including waste-derived composites, alternative concrete systems, and other locally developed materials. Such standards will provide industry and public procurement authorities the confidence to specify homegrown alternatives.

7.3 University–Industry Innovation Clusters

Specialized eco-materials industrial clusters should be developed around regions with abundant agricultural and industrial waste resources. These clusters should connect universities, foundries, manufacturers and technology developers, enabling research outputs, patented equipment and processing technologies to move efficiently into industrial production. Such an ecosystem would transform waste streams into economic resources while creating employment and strengthening domestic manufacturing.

7.4 Academic Vision, Commercialization and Researcher Retention

University promotion and research evaluation should recognize not only publications and grants but also patents, prototypes, technology transfer, start-ups and commercially deployed products. Universities should establish pilot foundries, machine shops and materials-processing facilities that enable researchers to develop and demonstrate technologies at relevant scales. Above all, sustained technological self-reliance requires investment in people through competitive welfare, functional laboratories and research incentives that enable talented engineers and scientists to build their careers in Nigeria.

ACKNOWLEDGMENTS

1. Divine Gratitude

I begin by giving all glory, honour, and praise to the Almighty God, whose mercy, grace, wisdom, and guidance have sustained me throughout my academic and professional journey. Every achievement represented by this inaugural lecture is, to me, a testimony of His faithfulness. I remain deeply conscious that knowledge, opportunity, strength, and perseverance are gifts that transcend human effort. I therefore dedicate this milestone first and foremost to God, the ultimate source of wisdom and the One who has been my shield and constant companion throughout the journey.

2. Family Tributes and Memorials

I owe an immeasurable debt of gratitude to my entire family for their foundational role, constant love, and unyielding support across my personal life and academic career.

First, I express my deepest love and appreciation to my late father, **Dr. Sebastian Okwuoha Alaneme**, whose intellectual inspiration, unwavering care, support, and enduring lessons in hard work, discipline, modesty, and resilience shaped my early life. Remarkably, my interest in medical and health materials engineering grew partly from the pain of witnessing his deteriorating health in the later years of his life. His passing, just as I was beginning to establish myself as a young PhD holder, remains a profoundly sad memory. I pray for God's eternal mercy and the peaceful repose of his soul. To my dear mother, **Mrs. Louisa Alaneme**, I extend my heartfelt gratitude for her care, constant love, patience, and profound spirit of sacrifice. Her presence has truly taught me the true value of family life. May God continue to bless her with robust health of mind and body.

I look back on my formative years with deep gratitude to my late grandparents, **Mr. Alphonsus Duruesie Alaneme**, fondly called *Big Papa*, and **Mrs. Mary Alaneme**. Living with them during those formative years blessed me with abundant love, protection, and strong moral values that profoundly shaped my character and life philosophy. I also fondly remember my late grand-uncle, **Mr. Fidelis Alaneme**,

with whom I shared a particularly close and cherished bond. May their souls continue to rest in perfect peace.

To my beloved younger siblings—Ms. Antoinette Alaneme, Mrs. Phyllis Uzoma, Mrs. Ogechi Barnabas, Mrs. Edith Leonard-Emeka, Mr. Michael Alaneme, Ms. Lilian Alaneme, Mr. Gabriel Alaneme, Mrs. Ozioma Akintibubo, Mr. Ikenna Alaneme, Ms. Chioma Alaneme, Mrs. Lauretta Alaneme, and Ms. Helen Alaneme: I thank you all for being wonderful younger ones, for your openness to counsel, and for maintaining love and togetherness. In the same vein, I appreciate our mothers, the late Mrs. Agatha Alaneme and Mrs. Fidelia Alaneme, for their immense contributions to our family's peace and growth, praying that the Lord grants eternal rest to the soul of Mrs. Agatha Alaneme.

Furthermore, I thank my uncles and aunts—Engr. Vincent Alaneme, Mrs. Leticia Ogubuike, Mrs. Caroline Nnamadim, Mrs. Florence Ajaegbo, Mrs. Monica Nwaigbo, Mr. Christian Alaneme, and Mr. Augustine Alaneme—for keeping our family bond alive. May God continue to bless them and their homes.

With profound reverence and affection, I give tribute to the parents of my beloved wife: my late father-in-law, Sir Alphonsus Duru, and my mother-in-law, Lady Alphonsus Duru. I highly appreciate them for being good in-laws, and for their constant love, and unwavering support. May the Almighty Lord grant Sir Alphonsus Duru eternal rest, and may He continue to sustain all members of the Duru family. I warmly acknowledge the spouses of my siblings and their families—Mr. Nicholas Barnabas, Mr. Chike Uzoma, Mr. Leonard Emeka Iheanatu, Mr. Akintibubo, and Mrs. Ikenna Alaneme—for fostering togetherness and love, praying that the Lord continues to bless them.

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3. Educational Foundations and Academic Mentors

My academic journey began in the classrooms of Local Authority Primary School, Araromi-Apapa, Lagos, and continued through Trinity Secondary School, Apapa, and the University of Benin Demonstration Secondary School, Benin City. I remain grateful to the teachers, classmates, and communities of these institutions for instilling in me discipline, intellectual curiosity, perseverance, and the desire to pursue excellence. I also acknowledge the 1992 graduating sets of Trinity Secondary School and the University of Benin Demonstration Secondary School for the enduring bonds of friendship and camaraderie that have survived the passage of time.

At the undergraduate and postgraduate levels, I was privileged to encounter teachers who profoundly influenced the direction of my academic life. I acknowledge Prof. V.N. Nwoko, Prof. O.O. Onyemaobi, Prof. J.E.O. Ovri, Prof. C.N. Anyakwo, Prof. Obikwelu, Dr. U.H. Udomon, Dr. C.S. Nwobodo, and Engr. A.I. Ogbonna.
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I reserve a special place in my heart for my late PhD supervisor and academic mentor, **Prof. Celestine Monde Kamma**. His passing at a critical stage of my career left me with a profound sense of loss. I remain grateful to God for the privilege of having worked under his guidance. May his soul continue to rest in peace. I also sincerely appreciate Prof. B.O. Adewuyi for his supervisory contributions during my doctoral studies.

4. Postdoctoral Training and International Academic Networks
The trajectory of my global career growth was subsequently shaped by working with two legendary minds during my time as a visiting scientist at the Indian Institute of Science, Bangalore. I am deeply grateful to the Association of Commonwealth Universities for awarding me the Winston Titular Fellowship, which generously funded my stay in India. I owe sincere thanks to my host, Prof. Upadrasta Ramamurty, a global icon in the Mechanical Behaviour of Materials, and my co-host, Prof. Srinivasa Ranganathan, a true sage in Physical Metallurgy. Aligning their extraordinary scholarship with my foundational training allowed me to mature into my current specialization in Mechanical and Structural Materials Engineering.

5. Funding Bodies and Industry Partners
I express my deepest gratitude to all the funding bodies and organizations that have supported my research and academic development over the years. I thank the Federal University of Technology, Akure (FUTA) for its invaluable Staff Development Scheme. Special thanks go to the Carnegie Corporation of New York (through the Regional Initiative in Science and Education, RISE) for funding the African Materials Science and Engineering Network (AMSEN). This network enabled me to attend vital global and regional workshops and to co-supervise students from our regional partner institutions.

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The monumental efforts of the founding fathers of our department—Prof. O. T. Adepoju, Prof. O. O. Onyemaobi, Prof. J. O. Borode, Prof. J.A. Omotoyinbo, Prof. B.O. Adewuyi, and Prof. John Ade Ajayi—are deeply appreciated. Your labor of sacrifice is truly not in vain. May God continue to bless you and your wonderful families. I also warmly acknowledge our past academic, technical and administrative staff for their vital support during their stay in the department.

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I extend my sincere appreciation to the past Deans of the defunct School of Engineering and Engineering Technology (SEET), specifically: Prof. O.T. Adepoju, Prof. Emeritus O.C. Ademosun, Prof. O.C. Adegoke, Prof. S.A. Ogunlowo, Prof. J.O. Afolayan, Prof. M.O. Alatise, Prof. A.M. Akintunde, and Prof. P.K. Oke, for their leadership and contributions to the development of the school. I specially appreciate the incumbent Deans of the School of Infrastructure, Mineral and Manufacturing Engineering (SIMME) and the School of Electrical Systems Engineering (SESE), established following the restructuring of the former SEET, Prof. C.O. Akinbile and Prof. A.O. Melodi, respectively, for their exemplary leadership, purposeful administration, and commitment to institutional advancement. I am particularly grateful to Prof. M.O. Alatise, under whose deanship my journey into academic leadership began through school and university committee assignments, including service on the Academic Planning Committee. I also appreciate Prof. A.M. Akintunde and Prof. P.K. Oke for their dedication during their respective tenures.

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11. Tribute to Mentees and Research Alumni

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Working within modest institutional research infrastructure, this collective has contributed to an extensive body of scientific publications and demonstrated that globally competitive research can emerge from our laboratories through resilience, intellectual collaboration, and dedication. I dedicate this lecture to these exceptional scholars and pray that they continue to excel and make lasting contributions to academia, industry, and society.

12. Spiritual Foundation and Church Hierarchy

I owe profound gratitude to Almighty God, whose faith is the bedrock of my life and career. I deeply appreciate the Spiritual Directors who have guided my journey, particularly Rev. Fr. Leo Flynn, Rev. Fr. V. Omolakin, Rev. Fr. Omoniyi, Rev. Fr. Eric Akinboboye, Rev. Fr. Mathew Adetiloye, Rev. Fr. Michael Ogunniyi, Rev. Fr. Luke Amuleya, Rev. Fr. James Ailien, Rev. Fr. Oragbunam, Rev. Fr. Dr. Anthony Okonkwo, and Rev. Fr. Chiemeka Utazi, among others.

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13. Igbo-Sociocultural Associations

To the Ideato Welfare Association, Ondo State—the umbrella body for all sons and daughters of Ideato North and Ideato South Local Government Areas of Imo State residing in Akure: ably led by Mr. Chidi Onyekwere (Men's Wing) and Mrs. Nkechi Agaehi (Women's Wing), I thank you all deeply for your presence, shared kinship values, love, and constant welfare support. Your essential *Umunna* role in the diaspora is immensely appreciated.

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14. Neighbours, Friends and People of Goodwill

To my dear neighbours, friends, and all people of goodwill, I express my heartfelt appreciation for your friendship, kindness, encouragement, and steadfast support. Your goodwill, fellowship, and thoughtful gestures are deeply cherished. May the good Lord continue to bless you and your families abundantly.

15. Ancestral Foundation and Family Legacy

In engineering, a structure may appear magnificent above ground, but its ability to withstand load depends fundamentally on its foundation. The same is true of a life. My academic achievements are not solely the product of individual effort; they rest on generations of sacrifice, values, struggles, prayers, and opportunities that preceded me.

Today, I therefore honour my **ancestors and lineage**, whose strength and sacrifices created the foundation upon which I stand. I proudly stand on their shoulders and dedicate this honour to their enduring legacy. May their souls, and the souls of all the faithful departed, through the mercy of God, rest in peace. Amen.

16. The Living Family Finale

That same resilient bloodline flows into this room tonight, alive in my beautiful family. To my beloved children—Michelle Chisom, Jason Kamsi, Isabel Chimamanda, Jacqueline Ziora, and Jaden Zimchikachim—you are my daily joy and the reason I keep building for the future. The way you embody our family values of hard work, excellence, modesty, determination, and self-discipline fills my heart with immense pride. May the Lord continue to build you for great exploits and establish you in lives of purpose, excellence, and service, to the glory of His Holy Name.

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The Final Climax: A Manifesto for National Self-Reliance

Vice-Chancellor, Ma, distinguished colleagues and guests—this 206th inaugural address culminates a 26-year journey, demonstrating that FUTA can pioneer research at the global frontier. Sustainable materials design offers a pathway to technological advancement: Nigeria cannot import self-reliance; we must engineer it through homegrown knowledge and ingenuity.

To the Almighty God, who began this good work and brought it to fulfilment, be all glory, honour, power and praise, now and forever.

To God alone be the glory. Thank you for listening.

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APPENDIX

Table 1. Comparison of tensile properties (per ISO 18265 and EN 10346) and fracture toughness metrics of standard dual-phase (DP) steel grades

Grade	UTS (MPa)	YS (MPa)	YS/UTS	ε (%)	K_{IC} ($MPa.m^{1/2}$) (Casellas et al., 2017; Frómeta et al., 2020)
DP780	780-900	440-550	0.56-0.61	≥ 14	35-50
DP800	800-950	480	0.5-0.6	≥ 14	35-38
DP980	980-1100	550-700	0.5-0.71	≥ 10	30-38
Alaneme et al. (2010)	884	585	0.66	≈ 22	43.4

Table 2. Comparison of K_{IC} values from CNT-based and standard K_{IC} evaluations

Material System	CNT-based K_{IC} $MPam^{1/2}$	Standard K_{IC} $MPam^{1/2}$ (CT or SENB-based)
Normalized Baseline Steel (0.3C-	**31.18 $MPa·m^{1/2}$** (Alaneme, 2011a)	AISI 1040 carbon steel 0.33%C **33 MPa√m** (İriç et al., 2019)
Dual Phase Steels	4**3.4 $MPa·m^{1/2}$** (Alaneme, 2011a ~884MPa UTS)	DP800 (~800 MPa UTS) **45 – 55 $MPa·m^{1/2}$** DP980 (~1000 MPa UTS) **35 – 45 $MPa·m^{1/2}$** (Casellas et al., 2017; Frómeta et al., 2020)
Cu-based SMAs	**18-24 $MPam^{1/2}$** (0.05-0.1 wt.% Fe, B modified CuZnAl SMA) (Alaneme et al., 2017a)	**34-42 MPa√m** A Cu-Al-Be-Mn quaternary SMA (Shivasiddaramaiah et al., 2018).

	15.72-19.95 MPam$^{1/2}$ (0.1-0.4 wt.% Ni CuZnAl SMA) (Alaneme and Umar, 2018)	
Monolithic ceramic Reinforced AMCs	8.32 to 12.67 MPa·m$^{1/2}$ (10 wt.% Al_2O_3 AMC) (Alaneme and Bodunrin, 2013)	44200 aluminium reinforced with 10–20% Al_2O_3 Saffil fibres, K_{IC} - **12 MPa√m** (Szymczak & Kowalewski, 2013)

Table 3: Chemical Composition of Die Component

Imported Die Component									
C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %	Fe %
1.02	0.299	0.450	0.0057	0.014	< 6.0	4.47	6.73	0.041	80.88
Indigenous Die Component									
C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %	Fe %
0.972	0.297	0.199	<0.002	<0.0010	15.68	1.98	8.06	>0.80	71.89

Table 4: Chemical Composition of motorcycle sprockets

Imported motorcycle sprocket										
C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Fe
.73	.392	1.47	.015	.0055	.013	.021	.0022	.025	.015	97.10
Locally produced motorcycle sprockets										
C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Fe
.401	.285	.67	.029	.011	.071	.03	.0026	.002	.034	98.4

Table 5: Chemical Composition of proposed steel material

Before Carburizing										
C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Fe
.281	.25	.87	.03	.051	.084	.103	.016	.022	.024	98.269
After Carburizing										
C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu	Fe

.67	.24 8	.86 4	.0 3	.05 1	.08 3	.10 1	.01 6	.02 2	.02 1	97.89 4

Table 6: Hardness Values of the Sprocket Materials

Material Type	Locally Produced Sprocket	Imported Sprocket	Proposed steel (before carburizing)	Proposed steel (after carburizing)
Hardness (HRC)	32.3±0.55	45.8±0.24	23.4±0.46	44.5±0.62

Table 7. Foundational pillars and disciplinary sub-fields of Mechanical and Structural Materials Engineering

MECHANICAL AND STRUCTURAL MATERIALS ENGINEERING (The Master Architecture of Applied Matter)		
Materials Design & Manufacturing *(Synthesis, Processing, & Geometry)*	**Mechanics of Materials & Environmental Response** *(Physics of Instantaneous Response)*	**Life Span, Durability, & Failure Analysis** *(Structural Risk Mitigation)*
Micro-to-Macro Synthesis • Alloy design & microstructure engineering • Composite materials design • Smart & functional materials design • Materials design & characterization	**Constitutive Mechanics** • Mechanical behaviour & testing • Deformation mechanics • Computational solid mechanics • Constitutive modeling • Residual stress & distortion	**Material Degradation & Damage** • Fracture mechanics • Fatigue engineering • Corrosion & degradation • Tribology • Impact & protective structures and materials
Advanced Processing • Manufacturing processes • Additive manufacturing • Thermomechanical processing	**Time-Dependent & Dynamic Behaviour** • High-strain-rate dynamics • Structural damping • Anelasticity & viscoelasticity	**Diagnostics & Lifespan Assessment** • Structural integrity & life assessment • Non-destructive testing (NDT)

• Solidification & liquid metallurgy • Advanced joining & forming • Surface engineering & Coatings	• Dislocation dynamics & plasticity	• Structural health monitoring
Eco-systemic Design • Sustainable structural infrastructure materials • Sustainable materials & circular engineering • Engineering applications & sustainability	**Extreme Environments** • High-temp deformation & creep • Cryogenic & radiation environments • Environmental embrittlement & SCC	**Joints, Forensics, & Compliance** • Welding & joining integrity • Failure analysis & forensics • Standards, codes, & certification

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Professor Kenneth Kanayo ALANEME is an internationally distinguished Metallurgical and Materials Engineer specializing in Mechanical and Structural Materials Engineering. Ranked among Stanford University–Elsevier's top 2% of global scientists, his research advances sustainable load-bearing materials through materials design, mechanics, structural integrity, and circular engineering. He has made pioneering contributions to hybrid aluminium matrix composites, cost-effective fracture-toughness assessment, and copper-based shape-memory alloys. With over 230 publications, four patents, and supervision of numerous undergraduate and postgraduate students, he serves as FUTA's Director of Research and Development.