Development of Indigenous Aluminium-Based Composite Using Eggshell Ash as Reinforcement: Thermodynamic Modelling and Industrial Applications

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I. Executive Summary

This project proposes the development of indigenous aluminium-based composites (AMCs) reinforced with eggshell ash, an innovative approach to transform agricultural waste into high-value engineering materials. The initiative addresses the dual challenge of waste management and the high cost of conventional reinforcements such as silicon carbide and alumina, which are largely imported.

The methodology combines eggshell waste collection and calcination**,** fabrication of aluminium composites via stir casting and powder metallurgy, and thermodynamic modelling using advanced software (ThermoCalc, FactSage) to optimise processing and predict phase stability. Comprehensive characterisation techniques (XRD, SEM/EDS, hardness, tensile, wear, and thermal testing) will evaluate material performance, while industrial validation trials will demonstrate suitability for automotive, aerospace, construction, and energy applications.

Expected outcomes include the development of low-cost, sustainable composites, validated modelling frameworks, published scientific outputs, and prototypes for industrial adoption. The project promotes a circular economy by converting waste to wealth, strengthens Nigeria's technological self-reliance, and supports national priorities in renewable materials, sustainable manufacturing, and industrial competitiveness.

With a funding request of ₦5,300,000 for 24 months, the project will deliver transformative materials innovation with direct socio-economic and industrial benefits.

Problem Statement

Nigeria's industrial sector encounters significant challenges due to its reliance on imported aluminium-based engineering materials. This dependency results in elevated costs for local industries involved in construction, transportation, and manufacturing, thereby diminishing their competitiveness and overall profitability. As these sectors endeavor to streamline expenses and enhance productivity, the importance of sourcing materials locally becomes increasingly pronounced. Concurrently, environmental issues are compounded by the disposal of waste eggshells, which are frequently overlooked as a resource and subsequently discarded. This disposal not only generates substantial waste management issues but also contributes to environmental degradation.

Addressing this dual challenge presents a unique opportunity for innovation within the industry. There exists a pressing necessity to develop cost-effective and environmentally sustainable reinforcement materials that can improve the properties of domestically produced aluminium composites, making them suitable for diverse engineering applications. Such advancements would not only mitigate the economic burden of import reliance but also promote recycling and the upcycling of waste materials. By transforming discarded eggshells into valuable resources, Nigeria can move toward a more sustainable and efficient industrial landscape, paving the way for greener engineering practices and long-term environmental benefits.

Proposed Solution

This project proposes the development of aluminium matrix composites (AMCs) reinforced with processed eggshell ash. Using thermodynamic modelling, the optimal processing conditions for composite formation will be determined. The innovation lies in turning waste into wealth by converting eggshell waste into reinforcement materials that improve aluminium's mechanical, wear, and thermal properties for industrial applications.

Key Novelty and Significance of the Proposed Research

- **Utilization of Waste Eggshells as a Novel Bio-Derived Reinforcement Material:** This project pioneers the transformation of abundantly available eggshell waste, typically discarded as an environmental burden, into a high-value reinforcement for aluminium matrix composites (AMCs). By exploiting the calcium carbonate and calcium oxide content of eggshells, the research advances *waste-to-wealth* innovation and contributes to circular economy principles.
- **Integration of Thermodynamic Modelling for Process Optimization:** Advanced computational tools such as ThermoCalc and FactSage will be employed to predict phase stability, interfacial reactions, and optimal processing conditions. This modelling-driven approach reduces experimental uncertainty, enhances process efficiency, and ensures reproducible composite properties suitable for industrial applications.

  Development of Low-Cost, Sustainable, Indigenous Aluminium Matrix Composites for Strategic Industries

- By leveraging locally sourced agro-waste and aluminium, the project will create affordable and environmentally friendly AMCs. These composites hold significant potential in **automotive (engine parts, brake systems), aerospace (lightweight structures), construction (reinforced panels, roofing materials), and energy sectors (turbine blades, heat exchangers)**. The approach reduces import dependence, fosters industrial competitiveness, and aligns with national goals for sustainable development and technological self-reliance.

Anticipated Impact:

Reduced Reliance on Imported Reinforcement Materials: By utilizing eggshell ash as an alternative reinforcement, the project will significantly cut down dependence on costly imported ceramic powders, thereby saving foreign exchange and enhancing national self-reliance.

Job Creation Through Local Materials Processing: The establishment of a processing chain for eggshell waste collection, calcination, and composite fabrication will generate new employment opportunities across the value chain, particularly for youths and local industries.

Environmental Sustainability by Recycling Waste: The project promotes a circular economy by converting agro-waste that would otherwise contribute to landfill burden into high-value engineering materials, thus supporting sustainable development goals.

Industrial Applications in Strategic Sectors: The developed aluminium matrix composites (AMCs) will find wide applications in automotive (engine parts, brake pads), construction (roofing sheets, reinforcement materials), aerospace (lightweight structural components), and energy systems (heat exchangers, turbines), strengthening Nigeria's industrial competitiveness.

Total Funding Requested: ₦ 5,300,000

Project Duration: 24 months

II. Introduction

The Indigenous Aluminum-Based Composite Using Eggshell Ash as Reinforcement project pioneers a sustainable approach to materials development by harnessing eggshell ash, a byproduct of the food industry, as a reinforcement material in aluminum composites [1, 2]. With a focus on thermodynamic modeling and industrial applications, this endeavor promises multifaceted benefits [3].

At its core, the project delves into the thermodynamic intricacies of the aluminum-eggshell ash composite system [4]. Researchers use advanced computational techniques to unravel the system's phase stability, microstructural evolution, and thermodynamic properties. This fundamental understanding lays the groundwork for optimizing composite composition and performance.

Practical experimentation forms a pivotal aspect of the project's methodology. Material preparation involves processing eggshell waste to obtain ash particles of uniform size and morphology, which are then integrated into the aluminum matrix using established techniques like powder metallurgy or stir casting [5]. Comprehensive characterization studies, including X-ray diffraction, scanning electron microscopy, and differential scanning calorimetry, provide insights into the composite's microstructure, phase composition, and thermal behavior [6]. Mechanical testing, encompassing tensile, compression, and flexural tests, evaluates the composite's mechanical properties, such as strength, stiffness, and ductility.

Beyond the laboratory, the project extends its gaze towards industrial applications. Collaborations with industry partners enable the assessment of the composite's suitability for various sectors, including aerospace, automotive, and construction [7]. By evaluating factors like lightweighting potential, corrosion resistance, and thermal performance, researchers aim to identify niche applications and potential market penetration avenues.

Ultimately, the Indigenous Aluminum-Based Composite Using Eggshell Ash as Reinforcement project embodies a synergy of scientific inquiry and practical innovation [8]. By leveraging waste materials and cutting-edge research, it fosters sustainable materials development. It holds promise for addressing pressing industrial challenges, ushering in a new era of eco-friendly and high-performance composite materials.

Organization Overview

The team comprises materials scientists, metallurgical engineers, and industrial partners with experience in composite materials development, thermodynamic modelling, and sustainable materials processing. The team has previously worked on bio-waste valorisation and aluminium-based alloys.

Alignment with NASENI's Vision and Mission

The project aligns with NASENI's mandate to foster indigenous technology, reduce import dependency, and develop Nigeria's manufacturing sector. Specifically, it advances NASENI's strategic goals of **Creation** (new indigenous composites), **Collaboration** (industry-academia partnership), and **Commercialization** (industrial applications in construction, automotive, and aerospace).

Challenge Context:
NASENI seeks innovations that strengthen Nigeria's **manufacturing base, renewable material use, and sustainable industrial development**. This project addresses those goals by producing eco-friendly, cost-effective indigenous aluminium composites.

III. Problem Statement

Detailed Problem Description:

Nigeria currently relies heavily on the importation of advanced composite materials, particularly aluminium-based composites reinforced with ceramics such as silicon carbide and alumina. This dependence costs local industries millions of naira annually, drains foreign exchange reserves, and limits the country's capacity to achieve technological self-reliance in strategic sectors like automotive, aerospace, and construction.

Although aluminium is one of the most widely used metals due to its light weight and corrosion resistance, its mechanical performance is limited in demanding applications. In areas requiring high strength, wear resistance, and thermal stability, conventional aluminium alloys often fail to meet industrial requirements. As a result, industries resort to expensive imported composites, increasing production costs and reducing competitiveness.

At the same time, Nigeria generates large volumes of eggshell waste from households, poultry farms, bakeries, and food processing industries. With minimal recycling or reuse pathways, these shells are largely discarded, contributing to environmental pollution and landfill burden. Yet, eggshells are rich in calcium carbonate, which can be transformed into calcium oxide (CaO) through calcination, making them a promising bio-derived reinforcement material for aluminium composites.

The challenge, therefore, lies in addressing the dual problem of material import dependency and waste mismanagement through the development of indigenous, sustainable aluminium matrix composites reinforced with eggshell ash.

Target Beneficiaries:

The proposed project is designed to deliver benefits across multiple layers of Nigeria's industrial, research, and socio-economic landscape. By developing indigenous aluminium-based composites reinforced with eggshell ash, the initiative directly supports industries seeking affordable, high-performance materials, while also creating opportunities for knowledge transfer, innovation, and community development. The target beneficiaries include manufacturing industries, researchers and SMEs, as well as local communities, all of whom stand to gain from the waste-to-wealth conversion model, job creation, and enhanced industrial competitiveness that the project promotes.

Local Manufacturing Industries (Construction, Automotive, Aerospace, and Energy): These sectors will directly benefit from access to cost-effective, high-performance aluminium matrix composites (AMCs), reducing dependence on imported reinforcement materials and improving competitiveness.

Researchers, Startups, and SMEs Developing Sustainable Engineering Materials: The project will provide new data, methodologies, and material innovations that support further research, encourage industrial spin-offs, and stimulate small and medium-scale enterprises (SMEs) focused on indigenous composite production.

Nigerian Communities and the Wider Economy: Communities will benefit from a waste-to-wealth system, where eggshell waste is transformed into valuable products, leading to environmental cleanliness, new employment opportunities, and improved livelihoods. This contributes to broader socio-economic growth, poverty reduction, and sustainable development.

Current Solutions & Gaps:

Existing reinforcements include silica, fly ash, and synthetic ceramics. However, these are often imported, costly, and environmentally unfriendly. Eggshell ash offers a sustainable, locally available alternative with unique properties (CaO-rich composition), but its industrial application in aluminium composites is underexplored.

IV. Project Description & Innovation

Proposed Solution in Detail:

- Concept & Design: Process waste eggshells into ash, characterize them, and integrate them as reinforcement in aluminium composites. Thermodynamic modelling will predict reaction pathways, phase stability, and optimal reinforcement levels.
- Technological Aspect: Combines materials science, computational modelling, and industrial metallurgy.
- Uniqueness & Competitive Advantage: First indigenous application of eggshell ash in AMCs within Nigeria, with a circular economy approach.
- Scalability: Scalable to multiple industries due to availability of eggshell waste and demand for aluminium composites.

Goals & Objectives:

- **Overall Goal:** Develop indigenous aluminium-based composites reinforced with eggshell ash for industrial applications.
- **SMART Objectives:**

1. To investigate the thermodynamic properties of the aluminum-eggshell ash composite system.
2. To optimize the composition of the composite for enhanced mechanical and thermal performance.
3. To evaluate the feasibility of large-scale production and industrial applications of the developed composite.

Methodology/Approach:

1. Collection and Preparation of Eggshell Waste

The first stage involves sourcing raw eggshell waste from **poultry farms, restaurants, bakeries, and food processing industries**. Since eggshells contain organic membranes and impurities, they will be thoroughly washed, dried, and crushed.

Calcination Process

The dried shells will undergo calcination at **800–900 °C in a muffle furnace** to decompose calcium carbonate ($CaCO_3$) into calcium oxide (CaO), eliminating volatile matter and sterilizing the powder. The obtained ash will be ground and sieved into different particle size ranges (e.g., <45 µm, 45–75 µm) for reinforcement studies.

Justification: Controlled calcination improves phase purity and enhances the compatibility of the eggshell ash with the aluminium matrix.

2. Composite Fabrication

Two fabrication routes will be employed for robustness and comparative evaluation

a. Stir Casting Technique

- Aluminium ingots will be melted in a resistance furnace at 700–750 °C.
- Preheated eggshell ash (to prevent thermal shock) will be added in varying weight percentages (e.g., 2%, 4%, 6%, 8%).
- Mechanical stirring at **300–600 rpm** ensures uniform dispersion.
- The molten composite will then be poured into metallic moulds for solidification.

Advantages: Low cost, industrial scalability, and suitability for mass production.

b. Powder Metallurgy Technique

- Aluminium powders will be blended with eggshell ash powders using a ball mill to ensure homogeneity.
- The mixture will be compacted under high pressure (e.g., 400–600 MPa).
- Green compacts will be sintered at **550–600 °C** in a controlled atmosphere.

Advantages: Better control of reinforcement distribution, refined microstructure, and reduced porosity.

3. Thermodynamic Modelling

Thermodynamic modelling provides predictive insights into phase stability and reaction mechanisms between aluminium and eggshell ash.

Software Tools:

- *ThermoCalc* and *FactSage* will be employed to calculate Gibbs free energy, phase equilibria, and possible intermetallic formation.
- CALPHAD (Calculation of PHAse Diagrams) approach will guide the selection of processing parameters.

Focus Areas:

- Predicting reactions between Al and CaO (e.g., possible formation of Al_2O_3 or $CaAl_2O_4$ phases).
- Stability assessment of reinforcement at elevated temperatures.
- Simulation of solidification behaviour and microstructure evolution.

Significance: Modelling minimizes trial-and-error, saves resources, and strengthens the reliability of experimental results.

4. Characterization of Composites

A comprehensive suite of tests will be conducted to evaluate the developed composites.

- **Phase and Microstructure Analysis:**

    - *X-ray Diffraction (XRD):* Phase identification and crystallinity analysis.

    - *Scanning Electron Microscopy (SEM) with EDS:* Morphology, reinforcement distribution, and elemental composition.

- **Mechanical Testing:**

    - *Hardness Test (Brinell/Vickers):* To assess wear resistance.
    - *Tensile Test:* To evaluate strength, ductility, and stiffness.
    - *Impact Test:* To measure energy absorption capacity.

- **Tribological Testing:**

Ball-on-disc wear test to assess wear rate and coefficient of friction under varying loads and speeds.

- **Thermal Properties:**

Thermal conductivity and coefficient of thermal expansion to validate suitability for automotive/aerospace use.

5. Industrial Validation

To ensure real-world relevance, the developed composites will undergo pilot testing in collaboration with industry partners.

- **Automotive Applications:** Brake pads, pistons, and cylinder heads will be prototyped and tested for wear resistance and thermal stability.

- **Construction Applications:** Use in roofing sheets, window frames, and structural reinforcement components will be explored.

- **Performance Benchmarking:** Results will be compared with conventional composites reinforced with SiC and Al_2O_3 to demonstrate cost and performance advantages.

- **Feedback Loop:** Industrial engineers will provide feedback for refining composition, processing parameters, and scale-up potential.

V. Impact & Commercialisation

Anticipated Impact:

The successful execution of this project is projected to have a notable quantitative impact on Nigeria's economic and technological landscape. By developing a minimum of five industrial prototypes and generating 30 new jobs within the recycling and materials processing sectors, the initiative will directly contribute to job creation and industrial output. Furthermore, the anticipated 20% reduction in costs compared to imported reinforcements will improve the nation's balance of trade, potentially influencing the Gross Domestic Product (GDP) and Internally Generated Revenue (IGR) by promoting local production and reducing reliance on foreign goods.

Alignment with National Priorities:

Supports Nigeria’s goals of **economic diversification, sustainable industrialization, environmental sustainability, and job creation**.

Commercialization Strategy:

- **Market Analysis:** Nigeria’s aluminium industry imports millions of dollars’ worth of reinforcements annually. Local industries will benefit from reduced costs.
- **Go-to-Market:** Partnerships with aluminium foundries, automotive firms, and construction companies.
- **Business Model:** Raw material supply (ash), licensing technology, and spin-off SMEs.
- **IP Strategy:** Patent filing on composite formulation and processing techniques.
- **Future Funding:** Seek additional support from industry stakeholders, private investors, and international sustainability funds.

VI. Project Team

- **Team Lead:** Engr. Dr. Akinribide Ojo Jeremiah Metallurgical Engineer, with expertise in aluminium alloys.
- **Materials Scientist:** Engr. Dr. Anamu Silas, a specialist in thermodynamic modelling.
- **Industrial Partner:** [Company/SME], provides pilot testing facilities.
- **Graduate Researchers:** Mrs. Ojo Folashade Elizabeth, a specialist in experimental fabrication and testing.

Partnerships with universities and industry partners will strengthen implementation.

VII. Budget & Justification

ITEMS for Attention	Sourcing	Amount (₦)
Equipment		
Bale out Furnace	EMDI	400,000
Muffle Furnace	EMDI	400,000
XRD Machine	EMDI	400,000
Characterization		
SEM Machine	To be sourced outside EMDI	400,000
DFT modelling tools	To be sourced outside EMDI	400,000
MD modelling tools	To be sourced outside EMDI	400,000
Monte Carlo & Kinetic Monte Carlo tools	To be sourced outside EMDI	400,000
CALPHAD and Gibbs free energy tools	To be sourced outside EMDI	400,000
DSC Machine	To be sourced outside EMDI	400,000
Materials		
Al-7075	To be sourced outside EMDI	700,000
Egg Shell Ash	Indigenously Sourced	(Not quantified)
Silicon Carbide	To be sourced outside EMDI	700,000
Travel and Collaboration		300,000
Contingency 20%		1,260,000
Total Budget		**5,300,000**

VIII. Monitoring & Evaluation

The evaluation of this project will be conducted through a structured plan that includes quarterly progress reviews and independent technical audits. To measure success, the project will track key performance indicators (KPIs) such as the number of composite samples fabricated, the improvement in mechanical and thermal properties compared to baseline aluminum, and the number of industries engaged for pilot trials. Data for these evaluations will be collected from a variety of sources, including lab test results, industry surveys, and market data. Findings and progress will be documented and shared through biannual reports submitted to NASENI and other relevant stakeholders**.**

Conclusion:

The development of indigenous aluminum-based composites by utilizing eggshell ash as reinforcement. Through a combination of thermodynamic modeling, experimental investigations, and industrial collaborations, this project seeks to contribute to the sustainable utilization of waste materials while offering new opportunities for lightweight, high-performance materials in various industries.

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