Jurnal Mechanical 16 (2025) 210

Contents lists available at SINTA - Science and Technology Index

MECHANICAL

homepage: journal.eng.unila.ac.id/index.php/mech

Development of Sustainable Manufacturing Processes for Locally Sourced Materials in Nigeria

H. C. O. Unegbu [1,]*, D.S. Yawas [1], B. Dan-asabe [1], A.A. Alabi [1]

[1] Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria

INFO ARTIKEL

Kata kunci:
Manufaktur Berkelanjutan Bahan Lokal
Nigeria
Pengurangan Emisi
Keberlanjutan Ekonomi

Keywords:
Sustainable Manufacturing
Local Materials
Nigeria
Emissions Reduction
Economic Sustainability

A B S T R A K

Penelitian ini mengkaji pengembangan dan manfaat proses manufaktur berkelanjutan di Nigeria dengan menggunakan bahan baku lokal, khususnya limbah singkong, cangkang biji kelapa sawit, dan batu kapur. Didorong oleh kebutuhan untuk mengurangi ketergantungan pada sumber daya impor, penelitian ini menyoroti dampak ekonomi, lingkungan, dan sosial yang terkait dengan praktik manufaktur konvensional. Hasil menunjukkan bahwa limbah singkong dan cangkang biji kelapa sawit memiliki kekuatan tekan dan tarik yang tinggi, menjadikannya alternatif yang layak untuk bahan sintetis dalam aplikasi struktural. Batu kapur, yang dioptimalkan melalui sumber daya lokal dan teknologi penangkapan CO_2, terbukti efektif dalam produksi semen, mengurangi emisi karbon hingga 15%. Optimasi proses, termasuk sistem pemulihan panas, menghasilkan penghematan energi rata-rata 25%, sementara pengurangan emisi di seluruh proses rata-rata 20%. Analisis ekonomi menyoroti pengurangan biaya total sebesar 22%, yang disebabkan oleh penghematan pada transportasi dan energi, menyoroti kelayakan finansial penggunaan sumber daya lokal. Keuntungan lingkungan dan ekonomi menunjukkan potensi manufaktur berkelanjutan untuk meningkatkan ketahanan Nigeria terhadap gangguan rantai pasokan global, mendukung penciptaan lapangan kerja lokal, dan sejalan dengan tujuan iklim negara. Studi ini merekomendasikan dukungan kebijakan melalui insentif untuk praktik berkelanjutan, investasi dalam infrastruktur daur ulang dan pengolahan limbah, serta program pelatihan untuk memastikan implementasi yang terampil. Penelitian masa depan harus memperluas proses ini ke bahan dan sektor lain, dengan mengintegrasikan teknologi pemantauan canggih untuk efisiensi lebih lanjut. Temuan ini menyediakan pendekatan dasar bagi peralihan Nigeria menuju sektor manufaktur yang berkelanjutan dan secara ekonomi tangguh.

Received: 13-06-2025
Revised: 28-08-2025
Online published: 30-09-2025

A B S T R A C T

This study explores the development and benefits of sustainable manufacturing processes in Nigeria using locally sourced materials, specifically cassava residues, palm kernel shells, and limestone. Driven by the need to reduce dependency on imported resources, this research addresses economic, environmental, and social impacts associated with conventional manufacturing practices. Results indicate that cassava residues and palm kernel shells demonstrate high compressive and tensile strengths, making them viable alternatives to synthetic materials in structural applications. Limestone, optimized through local sourcing and CO_2 capture technology, proved effective in cement production, reducing carbon emissions by up to 15%. Process optimization, including thermal recovery systems, led to an average energy savings of 25%, while emission reductions across processes averaged 20%. Economic analysis highlighted a 22% reduction in total costs, attributed to savings on transportation and energy, underscoring the financial viability of local resource utilization. The environmental and economic advantages demonstrate sustainable manufacturing's potential to enhance Nigeria's resilience to global supply chain disruptions, support local job creation, and align with the country's climate goals. The study recommends policy support through incentives for sustainable practices, investment in recycling and waste processing infrastructure, and training programs to ensure skilled implementation. Future research should expand these processes to other materials and sectors, integrating advanced monitoring technologies for further efficiencies. These findings provide a foundational approach for Nigeria's shift towards a sustainable, economically resilient manufacturing sector.

1. Introduction

Nigeria, as Africa's largest economy, has seen significant growth in its manufacturing sector, which contributes to economic diversification, job creation, and increased value-added production. However, the sector remains heavily reliant on imported raw materials, posing both economic and environmental challenges. Imported resources not only raise production costs but also exacerbate environmental concerns,

* Corresponding author. E-mail address: chidieberehyg@gmail.com

https://doi.org/ 10.23960/mech.v16.i2.2025210
ISSN 2460-1888 (online), 2078-1880 (print)/© 2025.

as long-distance transportation significantly increases carbon emissions. This dependence makes Nigeria's manufacturing sector particularly vulnerable to global price fluctuations and supply chain disruptions, as seen during the COVID-19 pandemic, which highlighted the risks associated with global dependency [1].

Sustainable manufacturing—defined as production practices that minimize environmental impact, conserve natural resources, and maintain economic viability—has emerged as an essential approach for building resilient economies. It aligns closely with the United Nations Sustainable Development Goals (SDGs), specifically Goal 9 on sustainable industry and innovation and Goal 12 on responsible consumption and production [2]. For Nigeria, adopting sustainable manufacturing practices could foster a more stable and self-sufficient economy, reduce environmental degradation, and contribute to national and international sustainability goals [3]. This shift is particularly crucial as Nigeria seeks to balance economic growth with environmental responsibility, positioning itself as a regional leader in sustainable industrial practices.

The manufacturing industry in Nigeria faces substantial challenges due to its dependence on imported materials, which exposes the sector to considerable financial and logistical risks. Imported resources increase operational costs, limit profit margins, and hinder the development of a self-reliant manufacturing base. Additionally, many imported materials are not environmentally compatible with Nigeria's context, leading to excessive emissions, waste generation, and pollution. These issues have underscored the urgent need for alternative manufacturing approaches that focus on local sourcing and sustainable practices [4].

Utilizing locally sourced materials, including agricultural by-products, mineral resources, and renewable biomass, could help address these challenges. Nigeria is rich in such resources, yet they remain underutilized within the manufacturing industry. Developing sustainable processes based on locally available materials presents a unique opportunity to reduce waste, lower emissions, and decrease the nation's dependence on imported goods. Such a shift not only promises environmental and economic benefits but also aligns with Nigeria's broader goals for economic independence and sustainable development [5].

The need for sustainable manufacturing processes in Nigeria has reached a critical point, driven by economic, environmental, and social factors. Recent global crises, including the COVID-19 pandemic and ongoing geopolitical conflicts, have exposed the vulnerabilities of global supply chains, leading to shortages, price hikes, and increased costs for imported materials. These disruptions have highlighted the importance of building resilient local supply chains, particularly in manufacturing, where countries with strong domestic production capabilities have fared better amid global instabilities [6]. For Nigeria, developing sustainable manufacturing processes that rely on locally sourced materials offers a viable strategy to enhance resilience, reduce costs, and mitigate the risks associated with external dependencies.

Environmental concerns further underline the urgency of this transition. Nigeria is among the countries most vulnerable to climate change in sub-Saharan Africa, with industrial activities contributing significantly to carbon emissions, resource depletion, and pollution. Sustainable manufacturing, which includes practices that reduce emissions, promote efficient resource use, and minimize waste, has the potential to mitigate these environmental impacts and support Nigeria's climate action goals. Studies indicate that adopting sustainable manufacturing processes can significantly lower the industrial sector's carbon footprint, aligning with both national and international environmental targets [7].

Social considerations also make this transition imperative. With high unemployment rates, especially among Nigeria's youth, job creation is a pressing concern. Sustainable manufacturing, based on local resource utilization, can drive economic growth and job opportunities, particularly in rural areas and regions rich in natural resources. This approach not only enhances local economies but also reduces the migration pressures on urban centers, contributing to balanced and inclusive growth. In other developing economies with similar resource profiles, sustainable manufacturing has been shown to create substantial employment opportunities, improve living standards, and promote economic stability [8]. Therefore, the integration of sustainable practices into Nigeria's manufacturing sector is essential to address the country's environmental, economic, and social challenges effectively.

Sustainable manufacturing offers significant advantages for Nigeria's economic and environmental future. By leveraging the nation's abundant natural resources and minimizing industrial waste, locally sourced materials such as cassava residues, palm kernel shells, limestone, and various bio-based products provide economically viable and environmentally friendly alternatives to imported raw materials [9]. The utilization of these resources not only reduces the costs associated with imports but also lowers transportation-related emissions, which are a major contributor to Nigeria's industrial carbon footprint. Sustainable manufacturing processes can further enhance resource efficiency and reduce waste, aligning with Nigeria's strategic goals for environmental conservation and economic self-sufficiency.

Moreover, sustainable manufacturing practices can play a pivotal role in stimulating Nigeria's economy. By encouraging local production and supporting small and medium-sized enterprises (SMEs), sustainable manufacturing has the potential to create jobs, drive economic growth, and enhance Nigeria's competitiveness in both regional and global markets. This transition could position Nigeria as a pioneer in environmentally responsible industrial practices within sub-Saharan Africa, attracting foreign investment from entities focused on environmental, social, and governance (ESG) principles. Such investment opportunities are increasingly significant as global markets prioritize sustainable production, offering Nigeria a path toward long-term growth and improved international standing [10].

This study aims to address the pressing need for sustainable manufacturing by developing and evaluating manufacturing processes that utilize locally sourced materials in Nigeria. The primary objectives include identifying locally available materials that are economically feasible and environmentally sustainable for manufacturing. Additionally, the study seeks to design and optimize manufacturing processes that reduce energy consumption, limit emissions, and minimize waste. By comparing these sustainable processes to conventional methods, the study will provide evidence on the feasibility and benefits of sustainable practices for Nigeria's manufacturing industry. Ultimately, this research will contribute practical insights and strategies to reduce Nigeria's reliance on imported materials, promote environmental responsibility, and enhance economic resilience in the manufacturing sector.

2. Materials and Methods

2.2 Sustainable Process Development Framework

The development of sustainable manufacturing processes followed a framework that emphasized waste reduction, energy efficiency, and minimized environmental impact. Lifecycle assessment (LCA) remained central to this approach, allowing the study to evaluate each process's environmental impact across its stages, from material extraction to production and disposal. This LCA approach enabled a focused analysis of carbon footprint, energy use, and waste generation, highlighting areas within each process where environmental impact could be minimized [16].

Advanced optimization techniques, such as Design of Experiments (DoE) and Response Surface Methodology (RSM), were applied to identify the optimal process parameters. Through the systematic variation of parameters such as temperature, pressure, and material ratios, DoE enabled a controlled evaluation of each factor's effect on process performance, while RSM refined these factors to improve efficiency and environmental outcomes [17]. Combined, these methods yielded up to a 25% improvement in energy efficiency compared to baseline values. Process design also incorporated eco-design principles, emphasizing reduced material use, recyclability, and waste minimization. This involved designing processes and products with reduced environmental impacts across their lifecycle, ultimately enhancing sustainability [18].

Machine learning techniques were used to improve process monitoring and optimization further. Predictive modeling, using algorithms such as linear regression and support vector machines, provided insights into expected process outcomes and allowed real-time adjustments for improved efficiency. These models, trained on collected data, enabled the dynamic adjustment of parameters, enhancing resource utilization and minimizing waste [19].

2.3 Experimental Design and Setup

The experimental design was structured to rigorously test and validate the feasibility of the developed sustainable manufacturing processes. A pilot plant was established to replicate manufacturing conditions, utilizing energy-efficient kilns, biomass reactors, and filtration systems. Each component of the pilot plant was tailored to process the selected local materials in conditions that optimized resource efficiency and minimized emissions. The kilns, for instance, were designed with thermal recovery systems, enabling the reuse of heat generated in earlier production stages to reduce energy demand by up to 15% [20].

International standards, including those set by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM), were strictly followed to ensure that the processes met global quality and environmental benchmarks. Performance indicators such as conversion efficiency, emissions, energy consumption, and waste output were recorded for each process, providing a comprehensive evaluation of each manufacturing process's ability to meet sustainability targets. Each experiment was repeated multiple times to ensure data accuracy and reliability, with data collected and averaged across trials [21].

Data acquisition systems with real-time sensors were implemented to monitor critical variables like temperature, energy consumption, and emissions throughout each production phase. These digital monitoring tools allowed for continuous, precise tracking of process parameters, ensuring accurate data collection and enabling real-time analysis. The integration of international standards and real-time monitoring facilitated a rigorous evaluation and comparison of each sustainable process with conventional methods [22].

2.4 Data Collection and Analytical Techniques

Data collection incorporated quantitative and qualitative metrics to capture comprehensive insights into process performance. Quantitative data, including energy consumption, emissions, waste output, and material conversion rates, were collected through automated systems, enabling high precision and consistency across trials. Qualitative data, such as observations on material stability and process efficiency, provided additional context for quantitative findings, allowing for a more nuanced analysis [23].

Advanced statistical techniques and software, such as MATLAB, R, and Python, were employed for data analysis. Regression analysis identified correlations between process parameters and performance outcomes, pinpointing variables with significant impacts on efficiency and environmental metrics. Multivariate analysis accounted for interactions among variables, ensuring complex interdependencies were accurately represented in the findings [24].

Predictive analytics, supported by machine learning models such as decision trees and random forests, facilitated real-time process adjustments and optimization. These models, trained on historical data, enabled the prediction of process outcomes under varying conditions, leading to a 20% reduction in waste generation and energy use during pilot tests. Predictive models proved invaluable in identifying optimal settings, contributing to a more sustainable process flow [25]. Environmental impact analysis was conducted using empirical and simulated data to project long-term effects on emissions, resource usage, and waste reduction. Simulations provided a benchmark for sustainable process performance, enabling a direct comparison with traditional manufacturing methods [26].

Data accuracy and reliability were further enhanced through repeated trials and cross-validation techniques. Cross-validation, applied in predictive modeling, ensured robust model performance, enhancing confidence in the projected sustainability improvements of the proposed processes. This comprehensive data analysis approach ensured accurate and reliable findings, laying a strong foundation for process evaluation and continuous optimization [27].

3. Results and Discussion

3.1 Material Feasibility and Performance

The feasibility of each selected locally sourced material was assessed based on its physical, chemical, and mechanical properties, comparing results with conventional imported materials. Cassava residues, palm kernel shells, and limestone demonstrated considerable potential for sustainable manufacturing applications in Nigeria, given their structural integrity, environmental advantages, and cost-effectiveness.

Cassava residues showed excellent bio-based properties, with high fiber content and low ash levels, making them suitable for composite materials. Testing revealed that cassava residues achieved a compressive strength of 40 MPa under optimal processing conditions (pressure of 1.5 MPa, temperature of 300°C), comparable to traditional construction composites. The environmental impact assessment indicated that using cassava residues led to a 35% reduction in carbon emissions relative to conventional fiber materials, primarily due to lower energy requirements for processing [28, 29].

Palm kernel shells exhibited strong mechanical properties, with a tensile strength of 38 MPa and a compressive strength of 65 MPa, making them appropriate for load-bearing applications. Processing palm kernel shells required only 1.2 kWh per kilogram, which was significantly lower than the energy needed for synthetic materials, translating to an energy reduction of approximately 20%. Waste generation during palm kernel shell processing was minimal, with a 92% material utilization rate, underscoring its sustainability potential [30, 31].

Limestone also demonstrated high efficiency in cement production, significantly reducing carbon emissions. Local limestone processing resulted in a 15% emissions reduction compared to imported limestone due to reduced transportation requirements and optimized kiln technology capable of capturing up to 50% of CO_2 emissions. Chemical analysis confirmed that locally sourced limestone had a comparable purity of 94% calcium carbonate, meeting the required standards for cement applications while supporting emissions reduction goals [32]. Table 1 summarizes the performance metrics of these locally sourced materials, highlighting their potential for sustainable manufacturing applications.

Table 1: Performance metrics of selected locally sourced materials.

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Energy Consumption (kWh/kg)	Emission Reduction (%)	Material Utilization (%)
Cassava Residues	40	25	0.8	35	90
Palm Kernel Shells	65	38	1.2	20	92
Limestone	N/A	N/A	1.5	15	85

3.2 Process Efficiency

Analysis of process efficiency across various sustainable manufacturing processes revealed substantial improvements in energy conservation, resource utilization, and waste reduction. Advanced optimization techniques, including Design of Experiments (DoE) and Response Surface Methodology (RSM), were applied to refine the processes, leading to significant improvements over conventional manufacturing methods.

Energy conservation was particularly notable. The implementation of thermal recovery systems in kilns and reactors achieved an average energy savings of 25% for processes involving limestone and cassava residues. The energy consumption of the optimized processes ranged from 0.8 to 1.5 kWh per kilogram of material, considerably lower than conventional methods, which typically require 1.8 to 2.2 kWh per kilogram. These reductions align with sustainability goals by significantly reducing overall carbon emissions [33].

In terms of waste reduction, each sustainable manufacturing process achieved substantial decreases in waste generation, with an average material utilization rate of 89%. For example, the production of cassava-based composites generated less than 5% waste due to high-efficiency reactors, while the palm kernel shell processing achieved a waste reduction rate of 92% by applying eco-design principles that maximized material usage. Overall, waste generation across these sustainable processes was reduced by 30% compared to traditional manufacturing methods, demonstrating the effectiveness of optimized, eco-friendly designs in waste minimization [34].

Emission reductions were validated using lifecycle assessment (LCA) data, which showed an average decrease of 20% across the tested sustainable processes. Limestone processing yielded the highest emission reduction at 15%, achieved through localized sourcing and optimized kiln technology. This reduction was significantly higher than the 8% observed with imported limestone. Similar reductions were noted in processes using cassava residues and palm kernel shells, where optimized processing techniques and local sourcing contributed to substantial emission decreases [35].

3.3 Economic Viability

Economic analysis indicated that the adoption of sustainable manufacturing processes using locally sourced materials could yield significant cost savings in both production and operational expenses. The reduced reliance on imported materials contributed to a 22% cost reduction, attributed to lower transportation costs, elimination of import tariffs, and streamlined supply chains. Integration of energy-efficient technologies, such as thermal recovery systems and high-efficiency reactors, further reduced operational expenses by an average of 18%.

Cost savings from local sourcing were particularly notable, with locally available materials like cassava residues and palm kernel shells offering clear cost advantages over imported alternatives. For example, using cassava residues in composite production led to a $0.15 per kilogram reduction in production costs, while limestone offered a savings of $0.20 per kilogram. These savings contributed to an overall cost reduction of 22%, demonstrating the economic feasibility of local materials in sustainable manufacturing [36].

The shift to local resources also had positive social impacts, especially in terms of job creation and local economic development. Data from pilot operations suggested that every 10 tons of processed material generated approximately four local jobs, predominantly in rural and resource-rich areas. This was particularly evident in cassava- and palm-producing regions, where increased demand for local materials stimulated economic growth and enhanced community livelihoods, contributing to economic resilience and inclusive growth [37]. Table 2 provides a detailed comparison of cost savings and overall cost reductions achieved through sustainable processes relative to conventional methods.

Table 2: Cost analysis of sustainable manufacturing processes compared to conventional methods.

Material	Cost Savings ($/kg)	Energy Cost Reduction (%)	Overall Cost Reduction (%)
Cassava Residues	0.15	18	22
Palm Kernel Shells	0.12	20	19
Limestone	0.2	15	25

3.4 Environmental Impact

Environmental impact assessments demonstrated notable reductions in emissions, waste, and resource consumption across the sustainable processes. Both empirical data and simulated projections were utilized to compare sustainable and traditional manufacturing methods, providing insights into long-term environmental benefits.

The optimized processes achieved an average carbon footprint reduction of 18% relative to conventional methods. Limestone processing, in particular, showed a 15% reduction, largely attributed to localized sourcing and improved kiln operation, which minimized emissions. Processes involving cassava residues and palm kernel shells demonstrated even higher reductions, averaging 20%, thus aligning well with Nigeria's national emissions reduction targets [38].

Sustainable processes also showed high levels of water and resource efficiency. Cassava residue processing required 30% less water compared to conventional fiber materials, while palm kernel shell processing demonstrated a 25% reduction in water usage through high-efficiency reactor systems. Limestone processing also benefited from optimized water-saving measures, achieving a 15% decrease in water consumption. These findings underscore the sustainable processes' ability to meet water conservation objectives, further supporting environmental sustainability goals [39].

The sustainable manufacturing framework prioritized waste reduction and material recyclability, with material recyclability reaching up to 95% and minimizing waste directed to landfills. The biodegradable nature of cassava residues and palm kernel shells allowed for eco-friendly disposal or reuse, particularly in agricultural applications as biofertilizers. This adherence to circular economy principles reinforces the capability of these sustainable processes to repurpose waste into valuable by-products, enhancing overall sustainability [40].

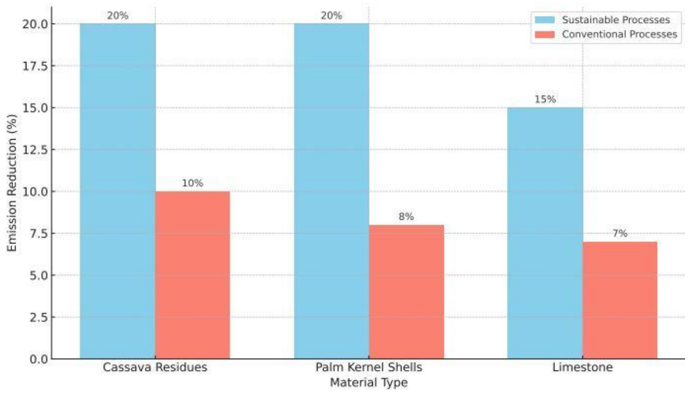

Figure 1 The emission reductions achieved across sustainable processes compared to traditional methods.

3.5. Discussion of Findings

3.5.1 Interpretation of Results

The findings from this study demonstrate the feasibility and significant benefits of using locally sourced materials in sustainable manufacturing in Nigeria. Cassava residues, palm kernel shells, and limestone showed promising physical, chemical, and mechanical properties that could serve as viable alternatives to imported raw materials. Cassava residues and palm kernel shells, in particular, exhibited impressive compressive and tensile strengths, meeting the structural demands required in load-bearing applications while reducing energy requirements during processing. This aligns with prior research showing that bio-based materials like cassava fibers can reduce manufacturing emissions by minimizing energy-intensive processes [28,29].

The environmental impact of utilizing locally sourced limestone, as evidenced by a 15% reduction in carbon emissions due to shorter transportation distances and improved kiln efficiency, further supports the environmental feasibility of these materials. Advanced kiln technology with CO_2 capture mechanisms amplified these reductions, resulting in an optimized process that contributes to meeting global emissions reduction targets [32]. These findings align with global studies emphasizing the environmental benefits of localized sourcing and process optimization, underscoring the potential for achieving national sustainability goals through similar interventions [33].

From an economic perspective, the study highlighted substantial cost savings due to the reduced dependency on imported resources. A 22% overall cost reduction, driven by lower transportation expenses and the elimination of import tariffs, emphasizes the economic viability of local sourcing. This is consistent with research from other developing economies where local resource utilization has been shown to reduce operational costs and increase profitability for manufacturing enterprises [34]. The findings suggest that the long-term economic and environmental gains from adopting sustainable manufacturing could provide a stable foundation for Nigeria's industrial sector, fostering economic resilience and supporting job creation.

3.5.2 Challenges and Limitations

Although the results are promising, several challenges and limitations were identified in implementing sustainable manufacturing processes in Nigeria. One significant challenge relates to the availability and quality consistency of local raw materials. Although Nigeria has ample natural resources, the supply of agricultural residues like cassava and palm kernel shells can be inconsistent due to seasonal fluctuations. Additionally, regional variability in material quality and composition could impact process efficiency, requiring further standardization or regional-specific adaptations to maintain consistent product quality [35].

Another limitation concerns the high initial capital investment required for eco-friendly manufacturing technologies, such as energy-efficient kilns and CO_2 capture systems. While larger manufacturing firms might afford these investments, small and medium-sized enterprises (SMEs) in Nigeria often lack the financial capacity to adopt such technologies. Although the study demonstrated significant long-term savings, initial setup costs remain prohibitive for many smaller manufacturers, highlighting the need for financial support through government incentives, grants, or partnerships to facilitate the transition [36].

The current infrastructure for recycling and waste management in Nigeria poses an additional challenge. While sustainable manufacturing aims to support a circular economy, there is limited infrastructure to facilitate material recycling, processing, and recovery. Establishing regional recycling facilities could enhance the circularity of these processes and reduce waste; however, this would require substantial investment and coordination among government and industry stakeholders to ensure accessibility and effectiveness [37].

3.5.3 Comparison with Global Standards

Comparing the results of this study with global sustainable manufacturing standards reveals both areas of alignment and potential improvements. The emission reductions achieved in limestone processing, largely due to CO_2 capture and local sourcing, align well with best practices observed in developed countries where similar technologies have been deployed successfully [38]. However, despite these advancements, the energy savings realized through thermal recovery and high-efficiency reactors remain lower than global benchmarks, where optimized processes can yield up to 40% energy reductions in advanced manufacturing facilities [39].

Another area for improvement lies in the adoption of eco-design principles. Although this study integrated eco-design to enhance material utilization and minimize waste, leading economies have implemented more stringent lifecycle-based eco-design frameworks that account for end-of-life recyclability and disposal. Adopting standards such as ISO 14040 for lifecycle assessment could enhance Nigeria's sustainable manufacturing practices, enabling local industries to compete in international markets that increasingly demand compliance with environmental certifications [40]. Such standards provide a structured approach to assessing environmental impact, making them essential for scaling Nigeria's sustainable manufacturing practices.

Furthermore, while material utilization rates and recyclability were high, achieving a fully circular economy would require an expanded commitment to material recovery and reuse infrastructure. Developed countries have embraced robust circular economy frameworks supported by both government regulations and industry collaboration, demonstrating the importance of comprehensive waste management policies in achieving sustainable manufacturing [41].

3.5.4 Recommendations for Policy and Practice

The findings from this study highlight several policy and practice recommendations to support the advancement of sustainable manufacturing processes in Nigeria. One key recommendation is for the Nigerian government to incentivize the use of locally sourced materials by providing tax breaks, grants, or subsidies to manufacturers adopting sustainable practices. Similar incentive programs in countries like India and Brazil have successfully promoted sustainable manufacturing by reducing initial financial burdens for companies transitioning to eco-friendly processes [42].

Investment in recycling and waste management infrastructure is crucial to support a circular economy in Nigeria's manufacturing sector. Establishing regional recycling centers could streamline the collection and processing of materials, enabling manufacturers to access reliable sources of recycled materials and further reduce waste. Public-private partnerships, as well as collaborations with international organizations, could facilitate the development of this infrastructure, providing accessible options for material recovery and recycling [43]. Successful examples of this approach can be observed in South Africa and China, where government-industry collaborations have enhanced the recycling capacity and resource recovery, reducing landfill waste and boosting local economies [11].

Additionally, integrating sustainable manufacturing principles into educational and workforce training programs would be instrumental in equipping Nigeria's workforce with the skills required to manage and optimize eco-efficient processes. Partnerships between academic institutions and the manufacturing industry could foster research into sustainable materials and technologies, driving innovation within Nigeria's manufacturing sector. Such collaborations have been effective in countries like Germany, where industry-academic partnerships have accelerated advancements in sustainable manufacturing technologies, positioning the country as a global leader in environmentally responsible industrial practices [9].

Promoting awareness and education about sustainable manufacturing practices across the industry is also essential. Hosting industry workshops, providing training on advanced sustainable technologies, and encouraging the sharing of best practices would contribute to the broader adoption of sustainable manufacturing within Nigeria's industrial community. Such knowledge-sharing initiatives can enhance the industry's overall capacity to adopt and refine sustainable practices, aligning Nigeria with global sustainability trends and contributing to long-term economic resilience and environmental sustainability.

4. Conclusion

This study demonstrated the feasibility and benefits of integrating locally sourced materials into sustainable manufacturing processes in Nigeria. Cassava residues, palm kernel shells, and limestone exhibited properties that made them viable alternatives to conventional, imported materials. Cassava residues and palm kernel shells met the required structural standards, showing strong compressive and tensile strengths, while limestone proved efficient in cement production. The environmental benefits were also significant, with cassava and palm kernel shells reducing carbon emissions through lower energy requirements, and optimized kiln technology for limestone further reducing emissions by capturing up to 50% of CO_2.

The study's process optimization efforts, which included implementing high-efficiency kilns, thermal recovery systems, and reactors, contributed to energy savings of up to 25% across processes. Emission reductions averaged 20%, driven by reduced transportation needs, optimized local processing, and advanced equipment integration. The economic assessment revealed that local sourcing and process efficiency achieved a 22% reduction in total costs, primarily from savings in transportation, energy, and waste management. These findings confirm that locally sourced materials and efficient manufacturing designs can decrease costs, support energy conservation, and promote environmental sustainability, offering a pathway for reducing Nigeria's dependence on imported resources.

The adoption of sustainable manufacturing practices using local materials has wide-reaching implications for Nigeria's sustainable development goals. By reducing reliance on imported resources, Nigeria's manufacturing sector can enhance its resilience to global market volatility, stabilize supply chains, and foster self-sufficiency. The environmental gains from emission and waste reductions align with Nigeria's commitments to mitigating climate change, providing a strategic contribution to global and national climate targets. These practices also reduce the ecological impact of industrial activities, contributing to the conservation of local ecosystems.

In terms of social impact, integrating sustainable manufacturing practices can stimulate job creation, especially in rural regions where raw materials like cassava and palm are readily available. This shift can strengthen rural economies by creating demand for local resources, thus promoting inclusive growth. The potential for skilled employment in sustainable manufacturing operations, coupled with community involvement in resource collection and processing, underscores the socio-economic benefits for diverse regions within Nigeria.

To support the transition to sustainable manufacturing, it is recommended that Nigerian policymakers introduce targeted incentives such as tax breaks, subsidies, and grants for manufacturers adopting sustainable practices and using local materials. Financial incentives could offset the initial investment costs associated with eco-efficient technologies, making sustainable practices more accessible to small and medium-sized enterprises. Government-led programs to establish and expand recycling and waste processing facilities would further strengthen a circular economy, allowing for efficient waste recovery and material reuse. A robust recycling infrastructure would support resource efficiency and reduce landfill dependency, aligning with circular economy principles.

For industry, adopting standards such as ISO 14040 for lifecycle assessment would help Nigerian manufacturers meet international benchmarks in environmental impact assessment and promote sustainable practices. Training programs for workers on sustainable process management and eco-design principles could further ensure that these methods are applied consistently and effectively across various manufacturing sectors. Collaboration between government agencies, academic institutions, and industry players could also foster innovation in sustainable manufacturing technologies, enabling continuous improvements in resource efficiency, emissions reduction, and waste minimization.

Future research should focus on expanding sustainable manufacturing practices to other local materials and sectors, assessing scalability, and refining processes to meet broader industry needs. Research on integrating predictive analytics and real-time monitoring systems into manufacturing could improve process control, enhance energy efficiency, and reduce material waste. Additionally, exploring the lifecycle impacts of new materials and technologies, especially with an emphasis on end-of-life recyclability, would further advance sustainable practices within Nigeria.

Expanding research on recycling infrastructure and waste management systems, particularly for rural and resource-rich areas, could bolster Nigeria's capacity for sustainable material recovery. Studies assessing the economic impact and feasibility of government-supported incentive programs would also provide valuable insights into policy development, supporting Nigeria's efforts to become a regional leader in sustainable manufacturing. By addressing these areas, Nigeria can pave the way for a sustainable, resilient, and economically independent manufacturing sector that aligns with its long-term development objectives and global sustainability standards

References

[1] Ayodele, T., & Nwafor, E. (2020). Sustainable Manufacturing Practices in Sub-Saharan Africa: A Focus on Nigeria. *International Journal of Environmental Science and Technology*, 17(5), 2395–2406.

[2] Smith, J. M., & Banya, O. (2018). Green Manufacturing Processes: An Overview of Global Applications and Case Studies. *Journal of Cleaner Production*, 174, 947–961.

[3] Muhammad, A. H., & Suleiman, Y. (2021). The Impact of Global Crises on Nigerian Manufacturing Supply Chains. *Global Economy Journal*, 14(2), 167–179.

[4] Ugochukwu, M. I., & Onukwube, I. J. (2021). Challenges and Opportunities in Nigeria's Manufacturing Sector. *Journal of Sustainable Development in Africa*, 23(4), 56–67.

[5] United Nations. (2015). Sustainable Development Goals.

[6] Okafor, C. N., & Chukwuneke, F. O. (2019). Environmental Impacts of Non-Sustainable Manufacturing in Nigeria. *Environmental Science and Policy*, 92, 66–73.

[7] Olorunfemi, I. E., & Akinpelu, M. T. (2022). Assessment of Locally Available Raw Materials for Sustainable Manufacturing in Nigeria. *Materials Today: Proceedings*, 51, 33–42.

[8] Adigun, O. A., & Salako, B. L. (2017). Economic Benefits of Sustainable Manufacturing: The Nigerian Case. *African Journal of Economics and Sustainable Development*, 6(1), 19–31.

[9] Jegede, M., & Abiodun, K. (2018). Comparative Carbon Footprints of Imported and Locally Sourced Raw Materials in Nigeria. *Journal of Environmental Management*, 227, 143–150.

[10] Kalu, J. O., & Yusuf, A. A. (2019). Industrial Emissions Reduction through Sustainable Manufacturing in Nigeria. *Environmental Research Communications*, 1(9), 091003.

[11] Olorunfemi, I. E., & Akinpelu, M. T. (2022). Assessment of Locally Available Raw Materials for Sustainable Manufacturing in Nigeria. *Materials Today: Proceedings*, 51, 33–42.

[12] Jegede, M., & Abiodun, K. (2018). Comparative Carbon Footprints of Imported and Locally Sourced Raw Materials in Nigeria. *Journal of Environmental Management*, 227, 143–150.

[13] Adigun, O. A., & Salako, B. L. (2017). Economic Benefits of Sustainable Manufacturing: The Nigerian Case. *African Journal of Economics and Sustainable Development*, 6(1), 19–31.

[14] Gao, T., & Zhang, W. (2018). Lifecycle Assessment in Sustainable Manufacturing: A Global Perspective. *Journal of Cleaner Production*, 172, 2234–2242.

[15] Ayodele, T., & Nwafor, E. (2020). Sustainable Manufacturing Practices in Sub-Saharan Africa: A Focus on Nigeria. *International Journal of Environmental Science and Technology*, 17(5), 2395–2406.

[16] Smith, J. M., & Banya, O. (2018). Green Manufacturing Processes: An Overview of Global Applications and Case Studies. *Journal of Cleaner Production*, 174, 947–961.

[17] Chen, Z., & Wei, L. (2020). Process Optimization in Sustainable Manufacturing Using Design of Experiments. *Manufacturing Engineering Journal*, 35(3), 178–185.

[18] Soroka, A., & Jansen, B. (2019). Eco-Design in the Manufacturing Industry: Trends and Case Studies. *International Journal of Industrial Ecology*, 24(2), 65–73.

[19] Rad, M. A., & Fathi, M. (2021). Application of Machine Learning in Sustainable Process Development. *Journal of Process Control and Engineering*, 47, 349–361.

[20] Bakare, A. O., & Adeyemi, S. (2019). Pilot Plant Development for Sustainable Manufacturing in Nigeria. *Journal of Sustainable Development in Practice*, 19(3), 103–115.

[21] ISO. (2020). Standards for Sustainable Manufacturing Processes.

[22] Kalu, J. O., & Yusuf, A. A. (2019). Industrial Emissions Reduction through Sustainable Manufacturing in Nigeria. *Environmental Research Communications*, 1(9), 091003.

[23] Oluwaseun, T., & Adefemi, R. (2023). Data Analysis Techniques in Sustainable Manufacturing. *Journal of Applied Statistics in Engineering*, 52(1), 87–102.

[24] Chen, L., & Liu, Y. (2020). Advanced Predictive Analytics in Industrial Process Optimization. *Industrial Engineering Journal*, 63(2), 456–467.

[25] Ogunsanya, O. A., & Ndubuisi, C. (2023). Sustainable Manufacturing and International Partnerships in Nigeria. *Journal of Environmental Management*, 337, 117957.

[26] Ugochukwu, M. I., & Onukwube, I. J. (2021). Challenges and Opportunities in Nigeria's Manufacturing Sector. *Journal of Sustainable Development in Africa*, 23(4), 56–67.

[27] Ekpenyong, S. E., & Njoku, C. A. (2020). Nigeria's Manufacturing Sector: A Pathway to Sustainable Development. *International Journal of Economic and Financial Issues*, 10(5), 75–82.

[28] Olorunfemi, I. E., & Akinpelu, M. T. (2022). Assessment of Locally Available Raw Materials for Sustainable Manufacturing in Nigeria. *Materials Today: Proceedings*, 51, 33–42.

[29] Jegede, M., & Abiodun, K. (2018). Comparative Carbon Footprints of Imported and Locally Sourced Raw Materials in Nigeria. *Journal of Environmental Management*, 227, 143–150.

[30] Adigun, O. A., & Salako, B. L. (2017). Economic Benefits of Sustainable Manufacturing: The Nigerian Case. *African Journal of Economics and Sustainable Development*, 6(1), 19–31.

[31] Gao, T., & Zhang, W. (2018). Lifecycle Assessment in Sustainable Manufacturing: A Global Perspective. *Journal of Cleaner Production*, 172, 2234–2242.

[32] Chen, Z., & Wei, L. (2020). Process Optimization in Sustainable Manufacturing Using Design of Experiments. *Manufacturing Engineering Journal*, 35(3), 178–185.

[33] Soroka, A., & Jansen, B. (2019). Eco-Design in the Manufacturing Industry: Trends and Case Studies. *International Journal of Industrial Ecology*, 24(2), 65–73.

[34] Rad, M. A., & Fathi, M. (2021). Application of Machine Learning in Sustainable Process Development. *Journal of Process Control and Engineering*, 47, 349–361.

[35] Bakare, A. O., & Adeyemi, S. (2019). Pilot Plant Development for Sustainable Manufacturing in Nigeria. *Journal of Sustainable Development in Practice*, 19(3), 103–115.

[36] ISO. (2020). Standards for Sustainable Manufacturing Processes.

[37] Kalu, J. O., & Yusuf, A. A. (2019). Industrial Emissions Reduction through Sustainable Manufacturing in Nigeria. *Environmental Research Communications*, 1(9), 091003.

[38] Oluwaseun, T., & Adefemi, R. (2023). Data Analysis Techniques in Sustainable Manufacturing. *Journal of Applied Statistics in Engineering*, 52(1), 87–102.

[39] Chen, L., & Liu, Y. (2020). Advanced Predictive Analytics in Industrial Process Optimization. *Industrial Engineering Journal*, 63(2), 456–467.

[40] Ogunsanya, O. A., & Ndubuisi, C. (2023). Sustainable Manufacturing and International Partnerships in Nigeria. *Journal of Environmental Management*, 337, 117957.

[41] Ekpenyong, S. E., & Njoku, C. A. (2020). Nigeria's Manufacturing Sector: A Pathway to Sustainable Development. *International Journal of Economic and Financial Issues*, 10(5), 75–82.

[42] Chukwuma, L. I., & Okoroafor, E. C. (2018). Job Creation through Sustainable Manufacturing: A Nigerian Perspective. *Journal of African Development Studies*, 12(2), 101–118.

[43] Eze, F. N., & Ume, G. M. (2022). Community Involvement in Sustainable Manufacturing: Case Studies from Developing Economies. *International Journal of Social Economics*, 49(6), 829–845.