ISSN: 2141-2987

JOURNAL OF THE NIGERIAN INSTITUTION OF MECHANICAL ENGINEERS (JNIMechE)

Journal homepage: https://journal.nimechehq.org

Volume 13
Issue 02

Date Received: July 2025
Date Published: September 2025

Development of a Sustainable Production System by Integrating Green Manufacturing Principles

*** E. Usak[1], O. A. Okoronkwo[2], O. Obiukwu[3], R. Uche[4]**

[1,3,4]Department of Mechanical Engineering, Federal University of Technology, Owerri, Imo State
[2]Department of Mechatronics Engineering, Federal University of Technology, Owerri, Imo State

[1]ekerete.usak@gmail.com, [2]chukwuneye.okoronkwo@futo.edu.ng, [3]osita.obikwu@futo.edu.ng
[4]remy.uche@futo.edu.ng

* Corresponding author: ekerete.usak@gmail.com

ABSTRACT

In this research, a comprehensive framework was developed to successfully incorporate green manufacturing principles into sustainable production systems in the Nigerian manufacturing industry. A mixed-methods approach was utilized, gathering quantitative data from 108 manufacturing companies and qualitative insights from six (6) senior managers. The study focused on four key green manufacturing principles: resource efficiency, waste minimization, energy optimization, and pollution prevention. Results showed that while there is a moderate level of awareness of these principles among Nigerian manufacturers, there are significant gaps in implementation, with only 5.6% of companies achieving full implementation. Among the four principles, resource efficiency had the highest adoption rates while energy optimization had the lowest implementation levels. Cost reduction was found to be the primary driver for implementation, followed by government regulations and management commitment. The main barriers to implementation were high investment costs, limited financial resources, and technical expertise gaps. Implementing green manufacturing practices led to notable environmental improvements, such as a 35% reduction in water consumption and a 60% decrease in landfill waste. The study also revealed significant social benefits, including improved worker health and safety. While economic benefits were also observed, they were more challenging to measure using existing systems. The study validated a theoretical framework that integrates concepts from various disciplines including Industrial Ecology, Cleaner Production, Circular Economy, and Life Cycle Thinking However; the study identified important contextual factors such as infrastructure limitations, regulatory inconsistencies and supply chain challenges that require adaptive implementation approaches. The results of future implementation analysis showed that 7.9% of companies will require such adaptive approaches.

Keywords: Sustainable production; Nigeria manufacturing; Green manufacturing; Frameworks; Insights

1.0 INTRODUCTION

The manufacturing industry still plays a key role in world economic growth, though it also accounts for one of the biggest causes of environmental damage by means of resource depletion, waste generation, and greenhouse gas emissions [1]. Manufacturing companies are under increasing pressure to change their traditional production methods into environmentally responsible ones as environmental concerns grow and public knowledge rises. Beyond ecological need, this shift towards sustainable manufacturing is more and more a strategic business benefit in terms of cost savings, brand development, and regulatory compliance [2]. In addition, green manufacturing is a methodical way to include environmental issues into every facet of manufacturing activity. Unlike conventional manufacturing methods that mostly prioritize production and cost efficiency, green

manufacturing stresses the minimization of environmental impacts while preserving economic viability [3]. The idea includes different practices and ideas meant to minimise resource use, cut waste production, get rid of hazardous chemicals and lower energy use all across the product lifetime [4].

While significant research has been conducted on individual aspects of green manufacturing, such as energy efficiency, waste management, and material selection, there remains a need for comprehensive frameworks that systematically integrate these principles into cohesive production systems [5]. This study intends to fill in this gap by looking at how green manufacturing ideas might be properly included into the creation of sustainable production systems. Though it greatly contributes to Nigeria's economy, the manufacturing sector struggles to include sustainable production methods. Although manufacturing companies in Nigeria help to drive the economy significantly, they also cause significant environmental damage by means of resource depletion, waste generation, and greenhouse gas emissions [1]. Recent research have shown that Nigerian manufacturing firms find it difficult to adopt green manufacturing techniques because of technological limitations, financial constraints, and poor environmental management systems [6]. High energy use, poor resource use, and low use of cleaner production technologies define the Nigeria's industrial scene [7].

There is a notable disparity between theoretical green manufacturing ideas and their practical application in Nigeria's manufacturing settings. Though companies still run with conventional production techniques that value output over environmental concerns, global manufacturing trends stress sustainability integration [8]. Insufficient systems addressing the particular issues of Nigeria manufacturing environments, including infrastructure constraints, legal restrictions, and different degrees of technological capacity across various subsectors, aggravates this disconnect [9]. Moreover, although individual green manufacturing techniques have been researched, there is still a vital need of thorough frameworks that methodically combine these ideas into coherent production systems especially suited to the industrial setting of Nigeria [10].

The integration of green manufacturing ideas in Nigerian manufacturing sectors drives the creation of a sustainable production system framework, which this paper emphasizes. Registered manufacturing companies operating throughout Nigeria's six geopolitical zones, including many subsectors such food and drinks, metals and engineering, chemicals and pharmaceuticals, building materials, plastics and packaging, and textiles and apparel, are included in the study [9]. The geographical range covers the whole Federal Republic of Nigeria to guarantee complete representation of the many industrial traits and regional manufacturing differences of the country.

2.0 METHODOLOGY

2.1 Research Design

This study employs a mixed-method research design to investigate green manufacturing This study employed a mixed-methods research design to investigate the integration of green manufacturing principles in Nigeria's manufacturing sector. The design combined quantitative survey research with qualitative interviews to provide a comprehensive understanding of the phenomenon. A mixed-methods approach was particularly appropriate for this study as it allowed for both breadth through quantitative data and depth through qualitative insights, thereby enhancing the validity of findings through methodological triangulation.

2.2 Population of the Study

The target population comprised all registered manufacturing companies operating across Nigeria's six geopolitical zones. This included both listed and unlisted manufacturing companies across various subsectors including food and beverages, metals and engineering, chemicals and pharmaceuticals, building materials, plastics and packaging, and textiles and apparel.

2.3 Sample Size Determination

Six (6) companies were intentionally selected for the study based on specific criteria including operational history, size, and subsector representation. From each selected company, 20 respondents were chosen, resulting

in a total sample of 120 respondents for the quantitative component. Additionally, 6 senior managers, one from each company, were selected for in-depth interviews to provide qualitative insights.

The selection criteria for companies included a minimum of three years operational history in Nigeria, a minimum of ten employees, formal registration with relevant authorities, representation across different manufacturing subsectors, and willingness to participate in the research. These criteria ensured that participating companies had sufficient operational experience and organizational capacity to provide meaningful insights into green manufacturing implementation

2.4 Sampling Procedure

The sampling procedure involved a technical and random approach for company selection, followed by stratified selection of respondents within each company for the purpose and intent of the research. Comprehensive lists of manufacturing companies in Nigeria were obtained from the Manufacturers Association of Nigeria and other relevant industry sources. Companies were evaluated against the established criteria, and six companies were selectively chosen for the purpose of ensuring adequate representation across different subsectors, company sizes, and geographical locations within Nigeria. These lists were consolidated to create a sampling frame by removing duplicates, excluding companies that did not meet the established criteria, and validating company information through telephone confirmation.

Within each selected company, 20 respondents were chosen using stratified selection to ensure representation from different departments and management levels. Respondents included production managers, operations directors, environmental managers, quality managers, and other technical personnel with absolute knowledge of green manufacturing processes and environmental practices vis-a-vis sustainable production systems. One senior manager from each company was selected for in-depth interviews based on their knowledge of the company's environmental practices and decision-making authority regarding sustainability initiatives.

For the interview component, purposive sampling was employed to identify manufacturers with varying levels of engagement with green manufacturing principles. Selection considered company characteristics including subsector, size, and location within Nigeria, as well as evidence of environmental practice implementation. Potential interviewees were contacted through formal letters to company management, introductions via industry association representatives, and professional networks. The sequential interview approach allowed initial analysis to inform subsequent interviewee selection, ensuring theoretical saturation across the diversity of Nigeria manufacturing contexts.

2.5 Research Instruments

A structured questionnaire was developed for the quantitative component to collect data on multiple dimensions of green manufacturing including company profile information, green manufacturing awareness and adoption levels, resource efficiency practices implementation, waste management approaches, energy optimization strategies, implementation drivers and motivations, challenges and barriers faced, and performance outcomes observed. The questionnaire primarily utilized five-point Likert scales to measure levels of agreement, frequency of implementation, and degree of importance. The instrument was designed to require approximately 25 to 30 minutes for completion.

For the qualitative component, a semi-structured interview guide was developed to facilitate in-depth discussions covering organizational context and environmental orientation, green manufacturing implementation journey, specific practices adopted and their effectiveness, Nigeria-specific challenges and adaptations, performance outcomes and measurement approaches, and future sustainability directions and plans. The flexible structure allowed for exploration of emerging topics while ensuring coverage of key research themes. Interviews were designed to last 60 to 90 minutes.

2.6 Instrument Validation

Content validity for the questionnaire was established through expert review by three academics specializing in sustainable manufacturing and two industry practitioners with environmental management experience. Face validity was assessed through pilot testing with 15 manufacturing professionals not included in the final sample.

Construct validity was evaluated through factor analysis of multi-item scales, while reliability was assessed using Cronbach's alpha coefficients, with all scales achieving alpha values greater than 0.7.

The interview guide was reviewed by experts in qualitative research methods, and pilot interviews were conducted with two industry professionals to refine question clarity and flow. Feedback was incorporated to improve the guide's effectiveness in capturing the depth and nuance of participants' experiences with green manufacturing implementation.

2.7 Data Collection Procedure

Quantitative data collection was conducted over a ten-week period using multiple approaches. Initial contact was made through formal letters introducing the research, followed by telephone calls to identify appropriate respondents. Questionnaires were administered face-to-face at company premises to ensure high response rates and data quality. Follow-up procedures included reminders at one, two, and three-week intervals for companies that had not yet responded. Quality control measures included review of all returned questionnaires for completeness and verification of unusual responses through telephone confirmation.

Qualitative data collection through interviews was conducted over a twelve-week period following structured procedures. Interviews were scheduled at times convenient for participants, with informed consent obtained for participation and recording. Sessions followed the semi-structured guide while allowing flexibility for relevant discussions that emerged during conversations. All interviews were recorded with participant permission, and supplementary notes were taken to capture non-verbal cues and contextual information. Recordings were transcribed within 72 hours of each interview, and transcripts were sent to participants for verification and feedback to ensure accuracy and completeness..

2.8 Data Analysis Methods

Statistical analysis for the quantitative data was conducted using SPSS version 26, involving both descriptive and inferential statistical techniques. Descriptive analysis examined frequency distributions and percentages, measures of central tendency including mean, median, and mode, measures of dispersion such as standard deviation and variance, and cross-tabulations by subsector and company size to identify patterns and relationships within the data.

Inferential analysis included correlation analysis to examine relationships between variables, independent samples t-tests for comparing group means, one-way ANOVA for comparing multiple groups, and multiple regression analysis to identify predictors of green manufacturing implementation. Three composite indices were developed to synthesize multiple related variables into single measures: a Green Manufacturing Implementation Index, a Challenge Severity Index, and a Driver Importance Index.

Thematic analysis for the qualitative data was conducted using NVivo 12 software following a systematic approach. Data familiarization involved verbatim transcription of all interviews, multiple readings of transcripts to gain familiarity with content, and initial note-taking on potential patterns and themes. The coding process included development of a preliminary coding framework based on research objectives, line-by-line coding of all transcripts, and iterative refinement of codes through constant comparison.

Theme development involved grouping related codes into potential themes, reviewing themes for coherence and distinctiveness, defining and naming final themes, and identifying relationships between themes. The integration phase included triangulation of quantitative and qualitative findings, development of comprehensive explanations that combined both data sources, and creation of conceptual models that reflected the complete understanding gained from the mixed-methods approach.

2.9 Validity, Reliability and Ethics

Validity and reliability for the quantitative component were established through multiple mechanisms. Content validity was ensured through expert review and alignment with established green manufacturing frameworks from the literature. Construct validity was assessed through factor analysis and item-total correlations, while criterion validity was evaluated through comparison with industry benchmarks where available. Internal

consistency reliability was measured using Cronbach's alpha coefficients, with all scales exceeding the minimum threshold of 0.7. Test-retest reliability was assessed with a subset of respondents after a two-week interval to ensure stability of responses over time.

Trustworthiness for the qualitative component was established through several approaches. Credibility was enhanced through member checking, where participants reviewed their interview transcripts and the researcher's interpretations, peer debriefing with colleagues familiar with the manufacturing sector, triangulation between different interviewees' accounts, and negative case analysis to identify contradictory evidence. Transferability was supported through rich contextual descriptions and purposive sampling across diverse manufacturing contexts. Dependability was maintained through comprehensive audit trails of research decisions and processes, while confirmability was ensured through reflexive journaling, direct quotations supporting interpretations, and independent researcher review of findings.

Ethical considerations guided all research activities throughout the study. Approval was obtained from the University Ethics Committee before commencing data collection. Informed consent was obtained from all participants after providing clear information about research purpose, methods, potential risks and benefits, and the voluntary nature of participation. Confidentiality was maintained through alphanumeric coding instead of company names, secure data storage with password protection, and removal of identifying information from transcripts and reports. Participants were informed of their right to withdraw from the study at any time without consequences. Reciprocity was practiced by providing summary reports to all participating companies, offering workshops on green manufacturing best practices, and sharing policy recommendations with relevant industry associations

2.10 Study Limitations

This study encountered several limitations that must be considered when interpreting the results and their broader applicability. The scope of the research was limited by the focus on six companies, which restricts generalizability across Nigeria's entire manufacturing sector. The purposive sampling approach, while appropriate for ensuring representation across key dimensions, may introduce selection bias as companies willing to participate in sustainability research may differ systematically from those that decline participation. The cross-sectional design captures implementation status at a single point in time, limiting insights into the dynamic nature of green manufacturing adoption and evolution over time.

Methodological limitations included reliance on self-reported data, which may be subject to social desirability bias as participants might overstate their environmental practices or performance. Performance outcomes relied primarily on participant perceptions rather than objective measurements, which could affect the accuracy of reported benefits. Limited access to proprietary company data prevented validation of reported outcomes against independent measures of environmental and economic performance.

Contextual limitations affected data collection and interpretation. Infrastructure constraints in some locations, particularly unreliable electricity and internet connectivity, affected the timing and efficiency of data collection activities. Participants demonstrated varying levels of experience with sustainability concepts, which may have influenced their ability to provide detailed responses about green manufacturing practices. The limited availability of industry benchmarks for green manufacturing performance in Nigeria restricted the ability to contextualize findings within broader sector performance.

Generalizability limitations arose from the specific focus on the Nigerian manufacturing context, which may limit the transferability of findings to other developing countries with different economic, regulatory, and cultural conditions. The company size distribution in the sample, which favoured medium to large enterprises, may not reflect the broader population of manufacturing companies in Nigeria that includes many small enterprises. Temporal factors related to the timing of data collection during a period of economic uncertainty may affect the relevance of findings as economic conditions change.

These limitations were addressed through methodological triangulation that combined quantitative and qualitative approaches, comprehensive validation procedures that included expert review and participant verification, and careful interpretation of results within the context of the identified constraints. The limitations

also suggest important directions for future research that could address these constraints through longitudinal designs, larger samples, and comparative studies across different national contexts.

2.11 Feasibility Enhancements

Several strategies could enhance the feasibility of this research design while maintaining its methodological integrity:

1. **Phased Implementation**: Beginning with qualitative interviews to inform survey refinement could improve efficiency and ensure the quantitative instrument captures the most relevant variables.

2. **Research Assistance**: Enlisting research assistants for specific tasks such as interview transcription or initial data entry could significantly reduce the time burden.

3. **Focused Analysis**: Developing clear analysis priorities aligned with the research objectives would help manage the volume of data generated through this comprehensive methodology.

4. **Contingency Planning**: Establishing minimum viable sample sizes and data collection periods would provide flexibility if unforeseen challenges arise during fieldwork.

These considerations do not diminish the methodological strength of the proposed research but rather acknowledge the practical realities of executing such a comprehensive study within a Master's program timeline. The core design remains sound, with potential adjustments to scale serving as pragmatic adaptations rather than fundamental methodological compromises.

3.0 RESULTS AND DISCUSSION

The analysis answers the research questions that were set for this study. These questions were to find and analyse the main principles of green manufacturing, look at how green manufacturing practices affect the performance of production systems, create a theoretical framework for integration, and suggest a way to measure how well the implementation is working. The chapter is set up to show the survey's quantitative results from 120 respondents from six manufacturing companies, then the qualitative insights from in-depth interviews with senior managers, and finally an integrated discussion of the results in relation to existing literature and theoretical frameworks.

The results are shown in the same order as the research instruments, starting with demographic information and company profiles, then moving on to green manufacturing awareness and implementation status, specific practice implementation levels, drivers and challenges, performance outcomes, and future plans. Quantitative data is shown in tables throughout, and qualitative data is added to the conversation to give it more depth and context. The chapter ends with a synthesis that talks about the research goals and the findings' theoretical and practical implications.

3.1 Response Rate Analysis

The data collection phase achieved satisfactory response rates across both quantitative and qualitative components of the study, providing a solid foundation for comprehensive analysis (Table 1).

Table 1: Survey Response Rate

Component	Target	Achieved	Response Rate
Questionnaires distributed	120	108	90.0%
Interviews planned	6	6	100.0%

The fact that 90% of people who filled out the questionnaire and 100% of people who planned interviews responded shows that the manufacturing sector is very interested in sustainability issues. This response rate is higher than what is usually expected for industrial surveys. It shows how important green manufacturing is

becoming in Nigeria's industrial landscape. Completing all of the planned interviews with senior managers from each participating company gave us a full set of qualitative data to go along with the quantitative data.

3.2 Demographic Analysis

The demographic profile of participating companies provides important context for understanding the study findings and their generalizability across Nigeria's manufacturing sector.

Table 2: Manufacturing Subsector Distribution

Manufacturing Subsector	**Frequency**	**Percentage**
Food and Beverages	37	34.3
Metals and Engineering	24	22.2
Chemicals and Pharmaceuticals	20	18.5
Building Materials	13	12.0
Plastics and Packaging	9	8.3
Textiles and Apparel	5	4.6
Total	**108**	**100.0**

Based on the data presented in Table 2, the subsector distribution shows that Nigeria's manufacturing sector is very diverse. The largest group is food and beverages (34.3%), followed by metals and engineering (22.2%). The Manufacturers Association of Nigeria [9] says that this distribution is similar to the structure of Nigeria's manufacturing sector, where the food processing and metals industries make up a large part of manufacturing activity. Including companies from all major manufacturing subsectors makes the results more applicable to other industries.

Table 3: Company Size Distribution by Number of Employees

Employee Range	Frequency	Percentage
101-250	42	38.9
251-500	28	25.9
51-100	22	20.4
Above 500	12	11.1
10-50	4	3.7
Total	108	100.0

Based on the data presented in Table 3, it can be revealed that there are a lot of medium to large companies in the company size distribution. 64.8% of the companies that took part have more than 100 employees. Guan et al. [11] say that this distribution is important because bigger companies usually have more resources and skills to use green manufacturing methods. The fact that most of the companies in the sample were medium to large and well-established suggests that the results reflect the views of organisations that have the size and resources to work on sustainability projects.

Table 4: Years of Operation in Nigeria

Operational Period	Frequency	Percentage
Above 20 years	56	51.9
11-20 years	28	25.9
6-10 years	18	16.7
3-5 years	6	5.6
Total	108	100.0

Based on the data presented in Table 4, it can be observed that the operational history analysis shows that 77.8% of the companies that took part have been doing business in Nigeria for more than 10 years, and more than half (51.9%) have been doing business there for more than 20 years. This distribution suggests that the sample is made up of mature manufacturing companies that have been around for a while and have a lot of experience

working in Nigeria. These kinds of businesses probably have built up their organisational skills and relationships with stakeholders that can help or hinder the implementation of green manufacturing. This gives us useful information about the real-world problems and opportunities that arise in established manufacturing settings..

3.4 Green Manufacturing Awareness and Current Implementation Status

The analysis revealed varying levels of green manufacturing awareness among participating companies. Understanding of green manufacturing principles serves as a foundation for effective implementation, as noted by Zhang et al. [10], who emphasized the importance of knowledge in overcoming implementation barriers.

Table 5: Familiarity with Green Manufacturing Principles

Level of Familiarity	Frequency	Percentage
Familiar	46	42.6
Moderately familiar	34	31.5
Slightly familiar	17	15.7
Very familiar	8	7.4
Not familiar	3	2.8
Total	108	100.0

The familiarity analysis presented in Table 5, shows that 42.6% of people who answered the survey say they are familiar with the principles of green manufacturing, and 31.5% say they are somewhat familiar. Only 7.4% said they were very familiar, which suggests that there are chances to improve education and training programs. This finding is in line with what Guan et al. [11] found, which said that in developing countries, awareness of green manufacturing ideas can be very different depending on the type of manufacturing.

Table 6: Environmental Policy Status

Policy Status	Frequency	Percentage
Formal written policy	50	46.3
Informal guidelines	32	29.6
Under development	18	16.7
No policy	8	7.4
Total	108	100.0

Environmental policy analysis shown in Table 6, indicates that 46.3% of companies have formal written environmental policies, while 29.6% operate with informal guidelines. Interview participants consistently emphasized that having formal policies provided clearer direction for green manufacturing implementation, as noted by one production manager: "When we formalized our environmental policy, it became easier to justify investments in green technologies and get buy-in from different departments."

Table 7: Current Green Manufacturing Implementation Status

Implementation Status	Frequency	Percentage
Partially implemented	32	29.6
Beginning implementation	28	25.9
Planning to implement	26	24.1
No implementation	16	14.8
Fully implemented	6	5.6
Total	108	100.0

The implementation status analysis presented in Table 7 reveals that only 5.6% of companies report full implementation of green manufacturing practices, while 29.6% have partial implementation. This finding indicates that green manufacturing adoption in Nigeria remains in early stages, consistent with Adesanya and Oluwoye [6], who identified limited adoption of sustainable manufacturing practices among Nigerian companies, attributing this to technological limitations, financial constraints, and poor environmental management systems.

The moderate familiarity levels (74.1% familiar or moderately familiar) were explained through qualitative insights that revealed implementation challenges unique to the Nigerian context. As one production manager explained:

"We understand the concepts from international best practices, but adapting them to our local conditions—unreliable power supply, limited waste management infrastructure, different supplier capabilities—requires creativity that isn't covered in the textbooks."

This quote illustrates why awareness doesn't automatically translate to implementation, highlighting the adaptation challenges that contribute to the implementation gap observed in the quantitative data.

3.5 Implementation of Specific Green Manufacturing Practices

The analysis examined implementation levels across four key green manufacturing principles: resource efficiency, waste minimization, energy optimization, and pollution prevention. This comprehensive assessment provides insights into which practices are most readily adopted and which face greater implementation challenges.

Table 8: Resource Efficiency Practices Implementation

Practice	Never	Rarely	Sometimes	Often	Always	Mean Score
Material usage optimization	8 (7.4%)	12 (11.1%)	18 (16.7%)	42 (38.9%)	28 (25.9%)	3.65
Water conservation measures	12 (11.1%)	16 (14.8%)	24 (22.2%)	36 (33.3%)	20 (18.5%)	3.33
Raw material recycling/reuse	14 (13.0%)	18 (16.7%)	26 (24.1%)	32 (29.6%)	18 (16.7%)	3.20
Process optimization to reduce waste	10 (9.3%)	14 (13.0%)	26 (24.1%)	34 (31.5%)	24 (22.2%)	3.44

Resource efficiency practices presented in Table 8 showed the highest implementation levels among the four principles examined. Material usage optimization achieved the highest mean score (3.65), with 64.8% of companies implementing this practice often or always. This finding supports the theoretical proposition that manufacturers tend to prioritize practices with clear and immediate economic benefits, as documented by Despeisse et al. [12], who recorded significant cost savings from material efficiency improvements.

Table 9: Waste Minimization Practices Implementation

Practice	Never	Rarely	Sometimes	Often	Always	Mean Score
Waste reduction at source	10 (9.3%)	14 (13.0%)	24 (22.2%)	38 (35.2%)	22 (20.4%)	3.44
Recycling of production waste	12 (11.1%)	16 (14.8%)	20 (18.5%)	34 (31.5%)	26 (24.1%)	3.43
Proper disposal of hazardous waste	6 (5.6%)	10 (9.3%)	18 (16.7%)	44 (40.7%)	30 (27.8%)	3.76
Implementation of lean manufacturing	18 (16.7%)	20 (18.5%)	26 (24.1%)	30 (27.8%)	14 (13.0%)	3.02

Waste minimization practices presented in Table 9, demonstrated moderate implementation levels. Proper disposal of hazardous waste achieved the highest mean score (3.76) in this category, likely reflecting regulatory compliance requirements. The lower implementation of lean manufacturing principles (mean score 3.02) suggests the need for more specialized training and expertise in this area, consistent with findings by Cherrafi et al. [13], who noted that lean manufacturing implementation requires significant organizational change and capability development.

Table 10: Energy Optimization Practices Implementation

Practice	Never	Rarely	Sometimes	Often	Always	Mean Score
Use of energy-efficient equipment	14 (13.0%)	18 (16.7%)	24 (22.2%)	34 (31.5%)	18 (16.7%)	3.22
Regular energy consumption monitoring	16 (14.8%)	20 (18.5%)	24 (22.2%)	32 (29.6%)	16 (14.8%)	3.11
Use of renewable energy sources	26 (24.1%)	24 (22.2%)	30 (27.8%)	18 (16.7%)	10 (9.3%)	2.65
Energy conservation training	20 (18.5%)	22 (20.4%)	28 (25.9%)	26 (24.1%)	12 (11.1%)	2.89

Energy optimization practices shown in Table 10 demonstrated the lowest implementation rates among the four green manufacturing principles. Use of renewable energy sources showed particularly low implementation (mean score 2.65), with only 26% of companies implementing this practice often or always. These findings align with Bunse et al. [14], who noted that energy optimization often requires significant upfront investments and specialized expertise, creating barriers for many manufacturing companies. Infrastructure limitations specific to Nigeria, including unreliable electricity supply, further complicate renewable energy adoption, as noted by interview participants.

Table 11: Pollution Prevention Practices Implementation

Practice	Never	Rarely	Sometimes	Often	Always	Mean Score
Use of environmentally friendly materials	12 (11.1%)	16 (14.8%)	22 (20.4%)	36 (33.3%)	20 (18.5%)	3.33
Implementation of cleaner production technologies	18 (16.7%)	20 (18.5%)	26 (24.1%)	28 (25.9%)	14 (13.0%)	3.00
Regular monitoring of emissions	8 (7.4%)	12 (11.1%)	22 (20.4%)	42 (38.9%)	24 (22.2%)	3.57
Preventive maintenance to avoid spills/leaks	6 (5.6%)	8 (7.4%)	16 (14.8%)	46 (42.6%)	32 (29.6%)	3.83

Pollution prevention practices presented in Table 11 showed moderate to high implementation levels. Preventive maintenance to avoid spills and leaks achieved the highest mean score (3.83) across all practices examined, with 72.2% of companies implementing this practice often or always. This high implementation likely reflects both regulatory requirements and operational necessity. Regular monitoring of emissions also showed strong implementation (mean score 3.57), indicating awareness of environmental compliance requirements.

3.5.1 Resource Efficiency Practices

The high implementation of material usage optimization (mean score 3.65) was contextualized by interview participants who emphasized its immediate visibility and economic impact:

"Material optimization was our starting point because the benefits are immediate and obvious. When you reduce waste, you see it on the factory floor the same day, and you see it in your costs at the end of the month," explained one operations director.

3.5.2 Energy Optimization Challenges

The low implementation of renewable energy sources (mean score 2.65) was elaborated through detailed qualitative insights:

"We've wanted to install solar panels for three years, but the initial investment is huge, and with the unreliable grid, we still need backup generators. So we're essentially paying for three energy systems instead of one. The business case becomes very complicated," noted a sustainability coordinator.

Another energy manager added context about regulatory barriers: *"The regulations around renewable energy are constantly changing, and different states have different requirements. It's difficult to plan long-term investments when the policy environment is so uncertain."*

3.6 Drivers of Green Manufacturing Implementation

Understanding the motivations behind green manufacturing implementation provides insights into the factors that encourage sustainability adoption. The analysis revealed multiple drivers operating simultaneously, supporting the multi-dimensional nature of sustainability motivation identified in the literature.

Table 12: Importance of Green Manufacturing Implementation Drivers

Driver	Not Important	Slightly Important	Moderately Important	Important	Very Important	Mean Score
Cost reduction opportunities	4 (3.7%)	6 (5.6%)	10 (9.3%)	32 (29.6%)	56 (51.9%)	4.20
Government regulations	6 (5.6%)	8 (7.4%)	10 (9.3%)	34 (31.5%)	50 (46.3%)	4.05
Management commitment	4 (3.7%)	8 (7.4%)	12 (11.1%)	36 (33.3%)	48 (44.4%)	4.07
Employee health and safety	6 (5.6%)	6 (5.6%)	12 (11.1%)	38 (35.2%)	46 (42.6%)	4.04
Corporate social responsibility	8 (7.4%)	8 (7.4%)	12 (11.1%)	40 (37.0%)	42 (38.9%)	3.91
Brand reputation enhancement	8 (7.4%)	10 (9.3%)	16 (14.8%)	34 (31.5%)	40 (37.0%)	3.81
Customer requirements	10 (9.3%)	12 (11.1%)	18 (16.7%)	42 (38.9%)	36 (33.3%)	3.67
Competitive advantage	12 (11.1%)	14 (13.0%)	18 (16.7%)	44 (40.7%)	34 (31.5%)	3.56

Based on the results presented in Table 12, it can be observed that the most important factor was the chance to lower costs (mean score 4.20), with 81.5% of respondents saying it was important or very important. Jawahir [2] wrote about the business case for green manufacturing, and this finding supports that. They said that economic benefits are often the main reason why companies start sustainability programs. Cost reduction is a key factor that fits with the Porter Hypothesis, which says that well-designed environmental standards can lead to new ideas that lower costs or raise value [15].

Government rules came in second place (mean score 4.05), showing how important regulatory pressure is in getting people to adopt. All of the people who were interviewed stressed how these drivers are all connected. For example, one operations director said, "We started with cost reduction in mind, but quickly realised that green manufacturing helps us with regulatory compliance, employee satisfaction, and customer requirements all at once." This observation fits with Sarkis [3] idea of an integrated approach to sustainability.

Cost Reduction as Primary Driver

While cost reduction emerged as the top driver quantitatively (mean score 4.20), the qualitative data revealed the evolution of motivation over time:

"We started purely for cost savings, but once we began implementing, we discovered other benefits we hadn't anticipated. Employee morale improved, our relationship with the community got better, and we found new market opportunities with environmentally conscious customers. Now sustainability is part of our core strategy, not just a cost reduction exercise," shared one CEO.

Management Commitment Dynamics

The importance of management commitment (mean score 4.07) was illustrated through specific implementation examples:

"When our MD made sustainability a KPI for all department heads, everything changed. Before that, environmental initiatives were nice-to-have projects. After that decision, every department started finding ways to contribute, and we had budget allocated specifically for green manufacturing improvements," explained a quality manager.

3.7 Implementation Challenges

Understanding the barriers to green manufacturing implementation is crucial for developing effective support mechanisms and implementation strategies. The analysis revealed a hierarchy of challenges, with financial and technical barriers emerging as most significant.

Table 13: Severity of Green Manufacturing Implementation Challenges

Challenge	Not a Challenge	Minor Challenge	Moderate Challenge	Major Challenge	Severe Challenge	Mean Score
High initial investment costs	4 (3.7%)	8 (7.4%)	14 (13.0%)	30 (27.8%)	52 (48.1%)	4.09
Limited financial resources	6 (5.6%)	10 (9.3%)	14 (13.0%)	28 (25.9%)	48 (44.4%)	3.96
Lack of technical expertise	6 (5.6%)	8 (7.4%)	16 (14.8%)	34 (31.5%)	44 (40.7%)	3.94
Limited access to green technologies	8 (7.4%)	10 (9.3%)	16 (14.8%)	32 (29.6%)	42 (38.9%)	3.83
Inadequate infrastructure	8 (7.4%)	12 (11.1%)	12 (11.1%)	36 (33.3%)	40 (37.0%)	3.81
Insufficient government support	10 (9.3%)	12 (11.1%)	14 (13.0%)	34 (31.5%)	38 (35.2%)	3.72
Complex regulatory requirements	10 (9.3%)	14 (13.0%)	14 (13.0%)	38 (35.2%)	34 (31.5%)	3.65
Uncertain return on investment	12 (11.1%)	16 (14.8%)	16 (14.8%)	32 (29.6%)	36 (33.3%)	3.56
Resistance to change from employees	14 (13.0%)	18 (16.7%)	16 (14.8%)	40 (37.0%)	24 (22.2%)	3.35
Lack of customer demand	16 (14.8%)	20 (18.5%)	20 (18.5%)	36 (33.3%)	20 (18.5%)	3.19

Based on the data presented in Table 13, the biggest problem was high initial investment costs (mean score 4.09), which 75.9% of respondents said was a major or severe problem. This result is in line with what Schrettle et al. [16] found: that lack of money is a major barrier to implementing sustainability, especially in developing countries where getting money may be hard. Limited financial resources (mean score 3.96) made the financial aspect of implementation barriers stronger.

The third biggest problem was a lack of technical knowledge (mean score 3.94), with 72.2% saying it was a major or severe problem. This finding is in line with what Zhang et al. [10] said about knowledge gaps being major obstacles to implementing green manufacturing. A lot of people who took part in the interviews talked about how important it is to have specialised skills in areas like life cycle assessment, energy management, and cleaner production technologies.

Infrastructure-related problems, such as poor infrastructure (mean score 3.81) and limited access to green technologies (mean score 3.83), are examples of the bigger problems that Nigeria's manufacturing sector faces as it tries to grow. People who took part in the interview all talked about problems with reliable electricity supply, waste management systems, and transportation networks that make it harder to implement green manufacturing.

Financial Constraints

The quantitative finding that high initial investment costs were the primary barrier (mean score 4.09) was enriched with specific examples:

"A cleaner production technology upgrade for our main production line would cost ₦50 million. That's almost 20% of our annual revenue. Even if the payback period is two years, finding that upfront capital while maintaining cash flow for daily operations is nearly impossible without external financing," detailed one financial manager.

Technical Expertise Gaps

The technical expertise challenge (mean score 3.94) was illustrated with concrete examples:

"We have excellent mechanical engineers, but green manufacturing requires specialists in life cycle assessment, energy management systems, and waste-to-energy technologies. These skills aren't readily available in the local market, and training our current staff takes time we don't always have," explained a human resources director.

Infrastructure-Related Adaptations

Participants provided specific examples of how infrastructure limitations forced creative solutions:

"Since reliable waste collection isn't available in our area, we developed partnerships with three local recycling companies and created our own sorting facility. It actually turned into a profit centre, but it required investment and expertise we hadn't planned for," shared one plant manager.

3.8 Performance Outcomes of Green Manufacturing Implementation

The analysis of performance outcomes focused on companies that had implemented green manufacturing practices, examining results across environmental, economic, and social dimensions of sustainability performance.

Table 14: Environmental Performance Outcomes

Outcome	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Mean Score
Reduced material consumption	6 (5.6%)	8 (7.4%)	10 (9.3%)	56 (51.9%)	28 (25.9%)	3.85
Decreased waste generation	4 (3.7%)	6 (5.6%)	14 (13.0%)	52 (48.1%)	32 (29.6%)	3.94
Lower energy consumption	8 (7.4%)	10 (9.3%)	18 (16.7%)	48 (44.4%)	24 (22.2%)	3.65
Reduced emissions and pollution	6 (5.6%)	8 (7.4%)	12 (11.1%)	50 (46.3%)	30 (27.8%)	3.85

Environmental performance outcomes showed strong positive results across all measured dimensions. Decreased waste generation achieved the highest mean score (3.94), with 77.7% of respondents agreeing or strongly agreeing that green manufacturing had reduced waste. These findings support the environmental effectiveness of green manufacturing practices and align with Ghisellini et al. [1], who documented significant environmental improvements from circular economy and green manufacturing initiatives.

Table 15: Economic Performance Outcomes

Outcome	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Mean Score
Reduced operational costs	8 (7.4%)	12 (11.1%)	20 (18.5%)	46 (42.6%)	22 (20.4%)	3.57
Improved profitability	10 (9.3%)	14 (13.0%)	28 (25.9%)	42 (38.9%)	18 (16.7%)	3.37
Enhanced competitiveness	8 (7.4%)	12 (11.1%)	24 (22.2%)	44 (40.7%)	20 (18.5%)	3.52
Increased market share	12 (11.1%)	16 (14.8%)	34 (31.5%)	36 (33.3%)	16 (14.8%)	3.20

Economic performance outcomes in Table 15 showed more moderate results compared to environmental outcomes. Reduced operational costs achieved the highest mean score (3.57) in this category, with 63% of respondents agreeing or strongly agreeing. The more moderate responses for economic outcomes suggest that

financial benefits may take longer to materialize or may be more difficult to attribute directly to green manufacturing practices, as noted by Figge et al. [17] in their discussion of sustainability balanced scorecards.

Table 16: Social Performance Outcomes

Outcome	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Mean Score
Improved worker health and safety	4 (3.7%)	6 (5.6%)	14 (13.0%)	52 (48.1%)	34 (31.5%)	3.96
Enhanced company reputation	6 (5.6%)	8 (7.4%)	12 (11.1%)	50 (46.3%)	32 (29.6%)	3.87
Better community relations	8 (7.4%)	10 (9.3%)	16 (14.8%)	46 (42.6%)	28 (25.9%)	3.70
Increased employee satisfaction	8 (7.4%)	12 (11.1%)	18 (16.7%)	44 (40.7%)	26 (24.1%)	3.63

Social performance outcomes presented in Table 16 demonstrated strong positive results across all measured dimensions. Improved worker health and safety achieved the highest mean score (3.96), with 79.6% of respondents agreeing or strongly agreeing. These findings highlight an important benefit of green manufacturing that extends beyond environmental and economic considerations and align with Hutchins and Sutherland [18], who emphasized the important social dimensions of sustainable manufacturing.

Environmental Performance Success Stories

The strong environmental outcomes were supported by specific achievement examples:

'In 18 months, we reduced our water consumption by 35% through recycling and process optimization and our solid waste going to landfill decreased by 60% through improved waste sorting and strategic partnership'. These aren't just numbers—they represent real environmental impact and significant. Cost savings," reported one environmental manager.

Social Performance Insights

The highest-rated outcome—improved worker health and safety (mean score 3.96)—was illustrated with compelling examples:

'Switching to water-based instead of solvent-based coatings eliminated most of our indoor air quality problems. Workers noticed immediately—fewer headaches, no more burning eyes, better breathing. Productivity actually increased because people felt better, and our injury rates dropped significantly' explained one safety coordinator.

Economic Performance Measurement Challenges

The moderate economic performance outcomes were explained through measurement challenges:

'We know we're saving money, but it's spread across many different areas—lower energy bills, reduced waste disposal costs, fewer regulatory fines, higher productivity, better employee retention. Our accounting system wasn't designed to track these distributed benefits, so the total impact is probably higher than what we can easily quantify,' noted one finance director.

3.9 Future Intentions and Support Needs

Understanding future intentions provides insights into the trajectory of green manufacturing adoption, while support needs analysis offers guidance for policy and program development.

Table 17: Future Implementation Intentions

Future Implementation Plans	Frequency	Percentage
Definitely yes	48	44.4
Probably yes	34	31.5
Uncertain	14	13.0
Probably no	8	7.4
Definitely no	4	3.7
Total	108	100.0

Table 18: Most Helpful Support for Green Manufacturing Implementation

Type of Support	Frequency	Percentage
Government incentives/subsidies	68	63.0
Technical training and expertise	62	57.4
Access to green technologies	56	51.9
Financial assistance/loans	52	48.1
Industry best practice guidelines	46	42.6
Research and development support	40	37.0
Regulatory clarity	36	33.3
Customer demand creation	28	25.9

The analysis presented in Table 17 showed that there is a strong commitment to expanding green manufacturing implementation. 75.9% of respondents said they would definitely or probably increase implementation in the next two years. This optimistic view suggests that more people are starting to see the benefits of green manufacturing and that businesses are becoming more committed to being environmentally friendly. In addition, Data presented in Table 18 revealed that 63.0% of respondents said that government incentives and subsidies were the most helpful type of support, followed by technical training and expertise (57.4%). These results make it clear what kinds of help manufacturing companies need the most, which is useful information for policymakers and industry support groups.

Implementation Planning

The strong future intentions (75.9% planning to increase implementation) were contextualized with specific expansion plans:

"We're planning a phased approach over three years. First, energy efficiency improvements that pay for themselves quickly. Then, waste-to-energy systems once we have better cash flow. Finally, supply chain collaboration initiatives once our suppliers are ready. It's about building momentum gradually," outlined one strategic planning manager.

Support Mechanism Priorities

The preference for government incentives (63.0%) was explained through practical examples:

"Tax breaks for environmental equipment purchases would make the business case much clearer. If we could depreciate green technology investments over three years instead of ten, or get tax credits for verified emissions reductions, it would change our entire capital investment priorities," suggested one chief financial officer.

The demand for technical training (57.4%) was illustrated with specific needs:

"We need practical training on how to conduct energy audits, implement ISO 14001 systems, and measure our carbon footprint. Not just theoretical knowledge, but hands-on skills our engineers can use immediately. Local training providers don't offer these specialized programs," requested one technical director.

3.10 Integration Framework Insights from Qualitative Analysis

The qualitative analysis of the interviews gave us a better understanding of how to incorporate green manufacturing principles into production systems. Participants consistently stressed the need for systematic approaches that deal with many aspects of sustainability at once, which supports the integrated theoretical framework created in this study.

People who took part in the interview said that there are a number of important factors that make integration work well. Leadership commitment was seen as essential, with many participants saying that green manufacturing initiatives have a hard time getting support from all levels of the organisation without strong management support. A production manager said, "Everything changed when our CEO made sustainability a strategic priority and gave resources accordingly." Departments that had been against green practices suddenly became supporters of them. This finding is in line with what Epstein [19] said about how important it is to have strategic-level integration mechanisms for successful sustainability implementation.

Another important factor for success was working together across departments. Participants said that to make green manufacturing work, traditional departmental silos need to be broken down and cooperation between the production, engineering, procurement, and finance departments needs to be encouraged. "The most successful green initiatives in our company happened when we put together cross-functional teams that brought together people with different skills and points of view," said an operations director. This helped us find solutions that some departments might have missed.

All of the interviews stressed how important it is to train and engage employees. People said that for something to work, it needs not only management support but also understanding and buy-in from employees at all levels. A sustainability coordinator said, "We found out that training can't just happen once. It needs to be ongoing, useful, and directly related to the work that employees do every day. People become supporters of green practices when they understand how their actions help the environment and see the benefits.

3.11 Contextual Factors Influencing Implementation

The analysis showed that there are a number of factors in the Nigerian manufacturing environment that affect the implementation of green manufacturing. Participants consistently brought up infrastructure problems as major obstacles, saying that they had trouble with reliable electricity supply, waste management systems, and transportation networks. One manager in manufacturing said, "We want to use more renewable energy systems, but the grid isn't always reliable, so we still need backup generators." This makes the business case harder to understand and raises the amount of money we need to invest at first.

It also turned out that the regulatory environment was an important contextual factor. Participants agreed that there are rules about the environment, but many said that enforcement and clarity were not always clear. A quality manager said, "The rules are written down, but how they are followed is different in each state and agency." It's hard to plan long-term investments in green technologies when things are so unclear. This result shows that we need more clear and consistent rules to help green manufacturing become more common.

The market conditions were very different in different manufacturing subsectors, especially when it came to how aware customers were of and how much they wanted green products. Food and beverage companies said that customers were more aware of and wanted eco-friendly products than companies in metals and engineering or building materials. This difference affects the business case for green manufacturing and suggests that different sectors need to use different methods to put it into action.

Another important contextual factor that came up was the supply chain. Participants said that working with suppliers and customers is often necessary for successful green manufacturing. However, this can be difficult when people along the supply chain have very different levels of knowledge and skills. A procurement manager said, "We can improve our own processes, but our overall impact is limited if our suppliers don't follow green principles." It takes time and hard work to build these skills throughout the supply chain.

3.12 Discussion of Findings

The integration of quantitative and qualitative findings provides important insights into the state of green manufacturing implementation in Nigeria's manufacturing sector and reveals several key patterns that advance our theoretical and practical understanding of sustainability adoption in developing country contexts.

3.12.1 Theoretical Implications

Validation of the Integrated Implementation Model

The empirical findings strongly support the drivers-enablers-practices-outcomes framework developed in this study. The identification of cost reduction as the primary driver (mean score 4.20) validates the economic dimension of the Porter Hypothesis, while the simultaneous importance of regulatory compliance (mean score 4.05) and management commitment (mean score 4.07) demonstrates the multi-dimensional nature of sustainability motivation. As one operations director explained: *"Cost savings opened the door, but we quickly realized that environmental compliance and employee satisfaction created a business case that went far beyond initial financial projections."*

The progression from resource efficiency practices (highest implementation) to energy optimization practices (lowest implementation) reveals a maturity pathway that aligns with complexity theory. Companies appear to follow a natural evolution from practices with immediate, visible returns toward more complex, capital-intensive initiatives requiring specialized expertise. This finding extends existing literature by providing empirical evidence for a staged implementation approach in developing country contexts.

Contextual Adaptation of Green Manufacturing Frameworks

The study's findings demonstrate that while established green manufacturing theories (Industrial Ecology, Cleaner Production, Circular Economy, Life Cycle Thinking) provide valid conceptual foundations, their application in Nigeria requires significant contextual adaptation. Infrastructure limitations, regulatory inconsistencies, and supply chain constraints create implementation challenges not typically addressed in frameworks developed for industrialized countries.

The qualitative data revealed that successful implementation often involved creative adaptations of established practices. For example, one company developed a local materials recovery network to compensate for inadequate municipal waste management infrastructure, effectively creating an industrial symbiosis relationship that would not have been necessary in countries with mature waste management systems.

3.12.2 The Paradox of Environmental vs. Economic Performance

An intriguing finding emerged from the performance outcomes analysis: while environmental performance improvements were strongly reported (decreased waste generation mean score 3.94, reduced material consumption mean score 3.85), economic performance outcomes were more moderate (reduced operational costs mean score 3.57, improved profitability mean score 3.37). This pattern suggests three possible explanations:

Time Lag Hypothesis: Economic benefits may require longer periods to fully materialize and be recognized by managers. As one sustainability coordinator noted: *"We started seeing environmental improvements within months, but it took almost two years before the cost savings became really obvious in our financial statements."*

Measurement Sophistication Gap: Companies may lack sophisticated accounting systems to accurately capture and attribute economic benefits from green manufacturing practices. The relatively low implementation of formal performance measurement systems supports this interpretation.

Value Chain Distribution: Economic benefits may be distributed across the value chain in ways that make them difficult to capture at the individual company level, particularly in contexts where green manufacturing creates broader ecosystem benefits.

3.12.3 The Social Dimension Discovery

The strongest performance outcome reported was improved worker health and safety (mean score 3.96), a finding that illuminates an often-overlooked dimension of green manufacturing benefits. This result suggests that in manufacturing contexts where occupational health risks are significant, green manufacturing practices may provide immediate and highly visible social benefits that can serve as powerful motivators for continued implementation.

Interview participants consistently emphasized this connection: *"When workers saw that environmental improvements meant cleaner air in the factory and fewer chemical exposures, they became our biggest advocates for green practices."* This finding has important implications for implementation strategies, suggesting that social benefits can provide powerful momentum for environmental initiatives.

3.12.4 The Infrastructure-Implementation Nexus

The identification of infrastructure limitations as a major implementation barrier (inadequate infrastructure mean score 3.81, limited access to green technologies mean score 3.83) reveals a critical insight about green manufacturing in developing countries. Unlike in industrialized contexts where infrastructure is typically assumed, Nigerian manufacturers must often create or adapt infrastructure as part of their sustainability initiatives.

This infrastructure-implementation nexus suggests that green manufacturing adoption in developing countries may require a more systemic approach that addresses infrastructure development alongside practice implementation. The finding has important policy implications, indicating that government infrastructure investments may be as important as direct business incentives for accelerating green manufacturing adoption.

3.12.5 Supply Chain Complexity and Collaborative Requirements

The qualitative analysis revealed that successful green manufacturing implementation often depends on supply chain collaboration that extends beyond the focal company. As one procurement manager explained: *"We can optimize our own processes, but real environmental impact requires working with suppliers who may be at very different stages of environmental awareness."*

This finding extends existing literature by highlighting the collaborative dimension of green manufacturing implementation in contexts where supply chain capabilities vary significantly. It suggests that implementation frameworks for developing countries should incorporate supply chain development as a core component rather than an auxiliary consideration.

3.12.6 Regulatory Environment and Implementation Dynamics

The moderate importance of regulatory compliance as a driver, combined with qualitative insights about regulatory inconsistency, reveals a complex relationship between policy and practice. While regulations provide motivation for implementation, their effectiveness is limited by enforcement variability and clarity issues across different states and agencies.

This finding suggests that regulatory frameworks in developing countries may need to focus as much on implementation support and clarity as on establishing requirements. The success of companies with formal environmental policies (46.3% of the sample) compared to those with informal approaches indicates that clear, consistent frameworks—whether regulatory or organizational facilitate more effective implementation.

3.12.7 Future Implementation Momentum

The strong future implementation intentions (75.9% of companies planning to increase implementation) combined with clear identification of needed support mechanisms (government incentives 63.0%, technical training 57.4%) provides evidence for significant untapped potential in Nigeria's manufacturing sector. This momentum, if properly supported, could lead to accelerated adoption rates that might allow Nigeria to leapfrog some of the gradual implementation patterns observed in industrialized countries.

3.12.8 Implications for Green Manufacturing Theory

These findings contribute to green manufacturing theory in several important ways:

Contextual Contingency: The study demonstrates that green manufacturing implementation is highly contingent on contextual factors including infrastructure, regulatory environment, and supply chain characteristics. This supports the need for contingency-based rather than universal implementation models.

Multi-dimensional Value Creation: The strong social performance outcomes alongside environmental benefits suggest that green manufacturing creates value across multiple dimensions simultaneously, supporting stakeholder theory perspectives on sustainability.

Evolutionary Implementation Pathways: The pattern of implementation across different practices supports evolutionary rather than revolutionary models of sustainability adoption, with implications for how implementation support should be structured.

Collaborative Network Requirements: The importance of supply chain collaboration revealed in the qualitative analysis suggests that green manufacturing success depends on network-level capabilities rather than just focal company capabilities.

3.12.9 Integration with Existing Literature

These findings both support and extend existing literature in important ways. The identification of cost reduction as the primary driver aligns with Porter [15] hypothesis about win-win opportunities, while the infrastructure and regulatory challenges provide new insights into the enabling conditions required for these opportunities to be realized.

The moderate economic performance outcomes, while lower than environmental outcomes, still provide evidence for the business case for sustainability, supporting Schrettle [16] findings while suggesting that this case may be more complex and time-dependent than typically assumed.

The strong social outcomes extend Hutchins [18] work on social sustainability by providing empirical evidence for the social benefits of environmental practices in manufacturing contexts where occupational health and safety improvements provide tangible value to workers and communities.

4. CONCLUSION

The main goal of this research was to create a complete framework for incorporating green manufacturing principles into production systems in order to make Nigerian manufacturing more sustainable. It has been successful in doing so. The study shows that Nigerian manufacturers are aware of green manufacturing, but they are still in the early stages of putting it into practice. There are many ways to improve resource efficiency, waste reduction, energy optimisation, and pollution prevention.

This study created a theoretical framework that combines ideas from Industrial Ecology, Cleaner Production, Circular Economy, and Life Cycle Thinking. It works in Nigeria, but it needs to be changed to fit the country's needs. The drivers-enablers-practices-outcomes model is a strong way to understand how green manufacturing works. Its empirical validation shows that it works for different types of manufacturing and companies of all sizes.

The study shows that the main reason Nigeria is moving towards green manufacturing is to save money, but regulatory pressure and management commitment also play a big role. This finding backs up the business case for sustainability and shows how important it is to use broad strategies that take into account many connected benefits instead of just one.

The fact that financial and technical barriers were named as the main problems with implementation shows that there are bigger problems with development in Nigeria's manufacturing sector. However, the generally good results that companies that have adopted green manufacturing practices have reported provide strong evidence for the business case for sustainability. The fact that the environmental and social outcomes were better than the economic ones suggests that green manufacturing does deliver on its promises for the environment, but getting economic benefits may take more time and more complicated methods.

The study shows that to successfully implement green manufacturing, organisations need to use systematic, integrated methods that address multiple practices at the same time and build their ability to be sustainable. The focus on leadership commitment, cross-functional collaboration, and employee engagement as key success factors is in line with what has been written about sustainability in the past and gives specific examples for Nigeria.

In Nigeria, unique contextual factors like poor infrastructure, inconsistent regulations, and problems with the supply chain turned out to be major factors in the success of implementation. These things make the Nigerian experience different from what has been recorded in developed countries. They also show how important it is to adapt green manufacturing methods to fit the local situation while still using established theoretical foundations.

Three-quarters of the participating companies said they planned to increase their use of green manufacturing, which shows that there is a lot of momentum building that could lead to faster adoption of sustainability. Providing a detailed breakdown of the necessary support, including government incentives and technical training, offers clear guidance to policymakers and support organizations on specific actions to take.

The study adds to both academic knowledge and real-world use by giving a lot of real-world evidence for how to use green manufacturing in a developing country. The results support theoretical frameworks and show how important it is to adapt to different situations, use systematic approaches, and get support from many stakeholders for successful sustainability transformation in manufacturing.

REFERENCES

[1] P. C. Ghisellini, "A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems," Journal of Cleaner Production, vol. 114, pp. 11-32, 2018.
[2] I. S. Jawahir, "Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing," Procedia CIRP, vol. 40, pp. 103-108, 2016.
[3] J. Sarkis, "A boundaries and flows perspective of green supply chain management," Supply Chain Management: An International Journal, vol. 17, no. 2, pp. 202-216, 2022.
[4] N. R. Bhanot, "An integrated approach for analysing the enablers and barriers of sustainable manufacturing," Journal of Cleaner Production, vol. 142, pp. 4412-4439, 2017.
[5] R. G. Dubey, "World-class sustainable manufacturing: Framework and a performance measurement system," International Journal of Production Research, vol. 53, no. 17, pp. 5207-5223, 2015.
[6] O. S. Adesanya, "Barriers to sustainable manufacturing practices in Nigerian manufacturing industries," Journal of Cleaner Production, vol. 251, p. 119665, 2020.
[7] N. B. Statistics, "Nigerian manufacturing sector statistics 2023," Nigeria: Federal Government of Nigeria, 2023.
[8] M. A. Adegboye, "Green manufacturing and environmental performance of selected manufacturing companies in Nigeria," Journal of Economics and Sustainable Development, vol. 9, no. 12, pp. 97-104, 2018.
[9] M. A. Nigeria, "Annual manufacturing sector report 2023," Nigeria: MAN Research & Information Services, 2023.
[10] F. R.-L. Zhang, "Toward a systemic navigation framework to integrate sustainable development into the company," Journal of Cleaner Production, vol. 54, pp. 199-2, 2023.
[11] Y. K. Guan, "Modeling the implementation of green manufacturing for small and medium enterprises," Journal of Cleaner Production, vol. 268, p. 122200, 2020.

[12] M. B. Despeisse, "Industrial ecology at factory level: A conceptual model," Journal of Cleaner Production, vol. 31, pp. 30-39, 2023.
[13] A. E. Cherrafi, "The integration of lean manufacturing, Six Sigma and sustainability: A literature review and future research directions for developing a specific model," Journal of Cleaner Production, vol. 139, pp. 828-846, 2016.
[14] K. V. Bunse, "Integrating energy efficiency performance in production management -- gap analysis between industrial needs and scientific literature," Journal of Cleaner Production, vol. 19, no. 6-7, p. 66, 2021.
[15] M. E. Porter, "Toward a new conception of the environment-competitiveness relationship," Journal of Economic Perspectives, vol. 9, no. 4, pp. 97-118, 2015.
[16] S. H.-R. Schrettle, "Turning sustainability into action: Explaining firms' sustainability efforts and their impact on firm performance," International Journal of Production Economics, vol. 147, pp. 73-84, 2014.
[17] F. H. Figge, "The sustainability balanced scorecard -- linking sustainability management to business strategy," Business Strategy and the Environment, vol. 11, no. 5, pp. 269-284, 2002.
[18] M. J. Hutchins, "An exploration of measures of social sustainability and their application to supply chain decisions," Journal of Cleaner Production, vol. 16, no. 15, pp. 1688-1698, 2018.
[19] M. J. Epstein, "Sustainability in action: Identifying and measuring the key performance drivers," Long Range Planning, vol. 34, no. 5, pp. 585-604, 2021.