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POLLUTION CONTROL, ENERGY EFFICIENCY, AND INDUSTRIAL PERFORMANCE: EVALUATING SUSTAINABILITY STRATEGIES IN PHARMACEUTICAL MANUFACTURING

SZENNYEZÉSCSÖKKENTÉS, ENERGIAHATÉKONYSÁG ÉS IPARI TELJESÍTMÉNY: A GYÓGYSZERGYÁRTÁS FENNTARTHATÓSÁGI STRATÉGIÁINAK ÉRTÉKELÉSE

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Kulcsszavak: *fenntartható gyártás; gyógyszeripar; energiahatékonyság; gazdasági növekedés; szennyezésellenőrzés; strukturális egyenletmodellezés*

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ABSTRACT

Sustainable manufacturing practices have gained increasing relevance as pharmaceutical industries seek to balance operational performance with environmental responsibility. Focusing on the Nigerian pharmaceutical manufacturing sector, this study investigates how such practices, including energy conservation, pollution control, renewable energy adoption, and recycling, may contribute to economic growth within pharmaceutical manufacturing firms. Using primary cross-sectional survey data collected in 2025 from 152 pharmaceutical manufacturing firms operating in Nigeria's major industrial corridors (Lagos, Ogun, and Kano States) and analyzed through Partial Least Squares Structural Equation Modeling (PLS-SEM), the study assesses the direct and indirect effects of sustainability practices on energy efficiency, which serves as a proxy for productivity-driven growth. The results reveal that pollution control and energy-saving practices have statistically significant positive effects on energy efficiency, while renewable energy technologies show strong indirect effects through improvements in economic performance. Interestingly, recycling initiatives are negatively associated with efficiency, suggesting that energy-intensive recycling processes in pharmaceutical production may offset potential sustainability benefits. The model explains approximately 92% of the variance in energy efficiency, indicating a high degree of explanatory power. These findings imply that the effectiveness of sustainability strategies in pharmaceutical manufacturing is context-specific, and that strategic alignment of sustainability actions with operational goals can enhance both environmental and economic performance. The study recommends that policymakers implement performance-based incentives and life-cycle assessment (LCA)–informed guidelines to support firms in selecting context-appropriate green strategies.

ABSZTRAKT

A fenntartható gyártási gyakorlatok egyre nagyobb jelentőségre tesznek szert, mivel a gyógyszeripari vállalatok arra törekednek, hogy az operatív teljesítményt összehangolják a környezeti felelősségvállalással. A nigériai gyógyszeripari feldolgozóiparra összpontosítva a tanulmány azt vizsgálja, hogy az olyan fenntartható gyakorlatok, mint az energiamegtakarítás, a szennyezésellenőrzés, a megújuló energiaforrások alkalmazása és az újrahasznosítás miként járulhatnak hozzá a gyógyszergyártó vállalatok gazdasági növekedéséhez. A kutatás 2025-ben gyűjtött, keresztmetszeti primer kérdőíves adatokra épül, amelyek 152, Nigéria fő ipari térségeiben (Lagos, Ogun és Kano államok) működő gyógyszergyártó vállalatot fednek le. Az adatelemzés részleges legkisebb négyzetek módszerén alapuló strukturális egyenletmodellezéssel (Partial Least Squares Structural Equation Modeling, PLS-SEM) történt.

A tanulmány a fenntarthatósági gyakorlatok energiahatékonyságra gyakorolt közvetlen és közvetett hatásait értékeli, ahol az energiahatékonyság a termelékenység által vezérelt növekedés proxyváltozójaként szolgál. Az eredmények azt mutatják, hogy a szennyezésellenőrzési és

energiamegtakarítási gyakorlatok statisztikailag szignifikáns, pozitív hatást gyakorolnak az energiahatékonyságra, míg a megújuló energia technológiák erőteljes közvetett hatásokat fejtenek ki a gazdasági teljesítmény javításán keresztül. Érdekes módon az újrahasznosítási kezdeményezések negatív kapcsolatot mutatnak az energiahatékonysággal, ami arra utal, hogy a gyógyszeripari termelésben alkalmazott, energiaigényes újrahasznosítási folyamatok ellensúlyozhatják a fenntarthatóságból eredő potenciális előnyöket.
A modell az energiahatékonyság varianciájának megközelítőleg 92%-át magyarázza, ami kiemelkedően magas magyarázóerőre utal. Az eredmények azt jelzik, hogy a fenntarthatósági stratégiák hatékonysága a gyógyszeripari gyártásban erősen kontextusfüggő, és hogy a fenntarthatósági intézkedések stratégiai összehangolása az operatív célokkal egyaránt javíthatja a környezeti és a gazdasági teljesítményt. A tanulmány azt javasolja, hogy a szakpolitikai döntéshozók teljesítményalapú ösztönzőket, valamint az életciklus-elemzésen (Life Cycle Assessment, LCA) alapuló iránymutatásokat vezessenek be annak érdekében, hogy támogassák a vállalatokat a kontextushoz illeszkedő, környezetbarát stratégiák kiválasztásában.

INTRODUCTION

Sustainable manufacturing has become a central concern in industrial policy and corporate strategy, particularly in sectors characterized by high resource intensity and significant environmental externalities. In recent years, the pharmaceutical industry has attracted increasing attention due to its environmental footprint, which is shaped by energy-intensive production processes, complex waste streams, and stringent regulatory requirements (Fiorentino et al., 2021; Dangelico & Vocalelli, 2022). Within this context, sustainability is increasingly viewed not only as an environmental obligation but also as a determinant of operational efficiency and long-term competitiveness.
This issue is especially salient in Nigeria, where pharmaceutical manufacturing plays a strategic role in healthcare provision, import substitution, and industrial development. Nigerian pharmaceutical firms operate in an environment marked by high energy costs, dependence on self-generated power, and evolving environmental regulation, conditions that heighten the relevance of energy efficiency and pollution control strategies (Olabi et al., 2022; Belkhir & Elmeligi, 2020). As a result, firms are progressively adopting sustainability-oriented practices, such as energy conservation, pollution abatement, renewable energy integration, and recycling, to improve efficiency, comply with regulatory expectations, and stabilize production costs (Dangelico & Vocalelli, 2022; Sharma & Verma, 2024).

Despite growing recognition of the importance of sustainable manufacturing, empirical evidence on its economic implications within Nigeria's pharmaceutical sector remains limited. While prior studies have linked green innovation and eco-efficiency practices to firm performance in manufacturing more broadly (Park & Kim, 2024; Fiorentino et al., 2021), less is known about the specific pathways through which sustainability initiatives translate into economic growth and operational efficiency in pharmaceutical production, particularly in emerging economy contexts. This gap is notable given the sector's reliance on energy-intensive processes, where energy use is often technologically embedded and difficult to substitute (Olabi et al., 2022).

Energy efficiency therefore represents a critical mechanism through which sustainability investments may influence firm-level economic outcomes. Recent literature suggests that improvements in energy efficiency can reduce operational costs, enhance productivity, and support competitiveness, especially when combined with pollution control and renewable energy technologies (Liu et al., 2022; Chen et al., 2023). However, the mediating role of energy efficiency in the relationship between sustainable manufacturing practices and economic growth has not been sufficiently examined in pharmaceutical manufacturing contexts.

This study addresses this gap by empirically analyzing how multiple dimensions of sustainable manufacturing influence economic growth, with particular emphasis on the mediating role of energy efficiency. Using firm-level survey data collected in 2025 from 152 pharmaceutical manufacturing firms located in Lagos, Ogun, Anambra, and Kano States, the study applies Partial Least Squares Structural Equation Modeling (PLS-SEM) to estimate both direct and indirect relationships among conservation practices, pollution control, renewable energy technologies, and economic performance (Gupta et al., 2023). This analytical approach enables a comprehensive assessment of how sustainability strategies are embedded within production systems and translated into measurable performance outcomes.

The Nigerian pharmaceutical industry provides a compelling empirical setting for this analysis due to its dual mandate of meeting rigorous quality standards enforced by the National Agency for Food and Drug Administration and Control (NAFDAC) while responding to environmental and cost pressures. Recent studies emphasize that sustainability initiatives in pharmaceutical manufacturing are increasingly intertwined with cost management, regulatory compliance, and market access, rather than being treated as peripheral or symbolic actions

(Sheldon, 2022; Singh & Kaur, 2023). Nevertheless, whether such initiatives yield consistent economic benefits remains an empirical question.

By situating energy efficiency as a central performance pathway, this study contributes to broader theoretical debates on eco-efficiency and sustainable industrial transformation in emerging markets. While sustainability has historically been framed as a potential trade-off with profitability, a growing body of evidence points to synergistic relationships in which environmental investments support innovation, operational resilience, and long-term growth (Fiorentino et al., 2021; Al-Ghazali & Afsar, 2023). This study advances that perspective by providing sector-specific evidence from pharmaceutical manufacturing, where environmental performance and operational efficiency are closely intertwined.

Overall, the study offers empirically grounded insights for pharmaceutical manufacturers, policy makers, and sustainability stakeholders seeking to align environmental objectives with industrial competitiveness in Nigeria. By identifying which sustainability strategies most effectively support energy efficiency and economic growth, the findings inform both managerial decision-making and the design of green industrial policies in emerging economies.

LITERATURE AND HYPOTHESES

Empirical Literature

In recent years, empirical research has proliferated on how sustainable manufacturing practices affect firm-level economic outcomes. Meta-analyses and large-scale surveys reveal consistent evidence that energy conservation and energy efficiency improvements are positively correlated with productivity gains, cost reductions, and enhanced competitiveness across manufacturing sectors (Belkhir & Elmeligi, 2020; Rahman & Hossain, 2023; Wang et al., 2022). Within the pharmaceutical industry, sustainability-oriented operational changes have been linked to measurable efficiency gains, particularly where energy-intensive processes dominate production (Bevilacqua et al., 2023; Liu et al., 2022).

From a resource-based view (RBV), these sustainability practices can be interpreted as firm-specific strategic capabilities, such as energy-efficient processes, pollution-control technologies, and skilled human capital, that are valuable, difficult to imitate, and capable of generating sustained competitive advantage. Investments in energy efficiency and pollution reduction thus function not merely as compliance activities but as productivity-enhancing resources that strengthen operational performance and cost leadership (Belkhir & Elmeligi, 2020; Fiorentino et al., 2021).

Multinational pharmaceutical firms such as Pfizer, Novartis, GSK, and AstraZeneca have documented waste reductions of up to 50%, energy savings approaching 40%, and carbon footprint declines of approximately 30% following the adoption of green chemistry, cleaner production, and recycling processes within clean manufacturing pipelines. These initiatives frequently rely on life-cycle assessment (LCA) frameworks that explicitly link environmental performance with cost efficiency and financial outcomes, reinforcing the Porter hypothesis that environmental regulation can stimulate innovation and competitiveness (Jiménez-González et al., 2016; Alder et al., 2022; Sheldon, 2022).

These findings are also consistent with eco-efficiency and environmental economics perspectives, which posit that minimizing resource inputs and environmental externalities per unit of output improves both environmental and economic performance. Life-cycle-based approaches operationalize eco-efficiency by enabling firms to identify cost-saving opportunities across production stages while reducing regulatory and environmental risks (Zhou et al., 2021; Laurenti et al., 2025).

Quantitative studies in emerging markets largely confirm these global findings. In Nigeria, firm-level analyses of quoted healthcare and manufacturing companies indicate that investments in employee training, community engagement, and environmentally responsible sourcing protocols yield positive effects on long-run financial sustainability and post-tax profitability. At the macro level, energy consumption has been shown to drive industrial growth, with Nigerian time-series studies demonstrating significant positive relationships between industrial energy use and manufacturing value added after controlling for labor and capital inputs (Pharma Manufacturing, 2024).

Institutional theory further explains these outcomes by emphasizing how firms respond to coercive and normative pressures arising from national regulations, stock exchange listing requirements, and international sustainability expectations. For exchange-listed pharmaceutical firms in Nigeria, compliance with environmental standards, waste regulations, and sustainability reporting norms creates incentives to formalize pollution control and energy-efficiency strategies as part of corporate governance structures (Wang et al., 2022; Rahman & Hossain, 2023).

Sector-specific evidence within Nigeria's pharmaceutical industry further supports these relationships. Cross-sectional studies of firms operating in Southwest Nigeria, including Emzor, May & Baker, Fidson, and Neimeth, show that lean manufacturing practices, such as inventory leanness, total productive maintenance, and systematic waste elimination, significantly improve corporate performance indicators, including cost leadership and productivity (Bevilacqua et al., 2023; Singh & Kaur, 2023). Complementary evidence from South–South Nigeria suggests that technological capability is strongly associated with market share, innovation output, and cost efficiency among pharmaceutical manufacturers, underscoring the role of integrated management and process upgrading in sustainable competitiveness (Al-Ghazali & Afsar, 2023).

Other empirical contributions present a more nuanced picture regarding recycling and circular economy practices. Qualitative studies of Nigerian manufacturing SMEs report that high implementation costs, limited technical expertise, and weak understanding of economic returns frequently constrain meaningful circular adoption, despite strong stated willingness to engage in sustainability initiatives. These findings align with broader international evidence suggesting that recycling initiatives may yield limited or even negative net energy-efficiency gains when not supported by appropriate technologies and life-cycle optimization (Belkhir & Elmeligi, 2020; Laurenti et al., 2025). Moreover, Nigerian manufacturing firms already operate with high specific energy consumption per unit of output due to unreliable grid electricity and heavy reliance on diesel generators, conditions that undermine competitiveness in the absence of targeted energy-efficiency interventions (Pharma Manufacturing, 2024).

Cross-country empirical studies provide additional perspective. Evidence from the European pharmaceutical sector indicates that R&D investment, export intensity, and skilled employment significantly predict national innovation performance, which in turn supports industrial growth and resilience (Li et al., 2024). In global manufacturing contexts, the integration of digital technologies has enabled average reductions of 15–20% in energy consumption and substantial improvements in resource utilization, highlighting the potential of digitalization as a sustainability accelerator (Mourtzis et al., 2024; Zhang et al., 2025; ISPE, 2025).

Within Nigeria, policy-oriented case studies emphasize ongoing efforts to institutionalize sustainability through instruments such as the Environmental Impact Assessment Act, harmful waste legislation, and pharmaceutical waste management guidelines. However, empirical assessments consistently identify enforcement gaps, infrastructure deficits, and financing constraints as key barriers to realizing economic and environmental synergies (Rahman & Hossain, 2023; Kumar et al., 2024; Madikizela & Chimuka, 2022).

Hypotheses Development

Effective pollution control strategies may serve as a crucial determinant of energy efficiency in the pharmaceutical manufacturing sector. Nigerian pharmaceutical firms, which often operate with aging infrastructure and inadequately regulated waste systems, face operational inefficiencies arising from emissions leakage, material losses, and regulatory non-compliance (Madikizela & Chimuka, 2022; Patil & Patil, 2024).

Drawing on eco-efficiency theory and the resource-based view, pollution control technologies, such as emission filtration systems, closed-loop production, and green chemistry, can be conceptualized as efficiency-enhancing assets that simultaneously reduce environmental externalities and improve resource utilization. By minimizing waste and energy losses, firms convert regulatory compliance into operational efficiency gains (Jiménez-González et al., 2016; Alder et al., 2022).

Empirical studies indicate that investments in pollution mitigation, such as emission filtration, closed-loop systems, and cleaner production technologies, can reduce resource waste, improve energy conversion efficiency, and strengthen regulatory compliance (Jiménez-González et al., 2016; Liu et al., 2022; Verma & Gupta, 2025).

As environmental regulation intensifies, firms that proactively adopt pollution control measures may also benefit from reduced compliance risks, reputational gains, and enhanced stakeholder legitimacy (Wang et al., 2022; Rahman & Hossain, 2023). From an institutional theory perspective, these benefits arise because firms align their operational practices with coercive regulatory pressures and normative expectations from investors, regulators, and international partners. Empirical evidence from pharmaceutical and process industries shows that pollution-abatement expenditure is positively associated with process efficiency and total-factor productivity, particularly when integrated into broader sustainability management systems (Al-Ghazali & Afsar, 2023; Elkington & Al-Shammari, 2024). Accordingly, the first hypothesis is proposed:

H1: Pollution control practices are positively associated with energy efficiency in Nigeria's pharmaceutical manufacturing sector.

Energy-saving initiatives, including energy audits, machine retrofitting, optimized HVAC systems, and preventive maintenance, may provide Nigerian pharmaceutical manufacturers with substantial cost reductions that translate into economic growth. These practices are particularly valuable in contexts characterized by volatile electricity supply and high energy tariffs (Bevilacqua et al., 2023; Pharma Manufacturing, 2024).

Consistent with environmental economics and RBV arguments, energy efficiency lowers marginal production costs and frees up financial resources that can be redeployed toward innovation, market expansion, and human capital development—key drivers of long-term economic performance. Empirical studies further suggest that efficiency-driven cost savings can be reinvested in innovation, market expansion, and workforce development, thereby enhancing long-run firm-level performance (Belkhir & Elmeligi, 2020; Mourtzis et al., 2024).

Evidence from emerging economies reinforces this relationship. Studies indicate that energy-conscious process design and efficiency-oriented investments exert both short- and long-term positive effects on productivity and output growth in manufacturing sectors (Li et al., 2024; Wang et al., 2022). Consequently, the second hypothesis is formulated as follows:

H2: Energy-saving practices are positively associated with economic growth in Nigeria's pharmaceutical manufacturing industry.

The adoption of renewable energy technologies, such as solar photovoltaic systems, hybrid generators, and bioenergy solutions, represents a potentially transformative strategy for achieving long-term sustainability and economic resilience in Nigeria's pharmaceutical sector. Given persistent grid instability and rising fossil fuel costs, decentralized renewable energy systems can improve production continuity while reducing emissions (Pharma Manufacturing, 2024; ISPE, 2025).

From an institutional and strategic sustainability perspective, renewable energy adoption allows firms to hedge against energy price volatility while signaling compliance with emerging global sustainability and reporting standards. Over time, these investments enhance firm resilience and competitive positioning. Although high upfront costs remain a barrier, empirical evidence suggests that firms that successfully integrate renewable energy technologies often realize long-term productivity gains and improved resilience to energy shocks (Mourtzis et al., 2024; Zhang et al., 2025).

Cross-country analyses further confirm that renewable energy adoption is positively associated with value-added growth in energy-intensive manufacturing sectors, supporting its relevance as a strategic sustainability lever (Wang et al., 2022; Li et al., 2024). These insights inform the final hypothesis:

H3: Adoption of renewable energy technologies is positively associated with firm-level economic growth in Nigeria's pharmaceutical manufacturing sector.

Figure 1 illustrates the conceptual model linking sustainability practices, economic growth, and energy efficiency in Nigeria's pharmaceutical sector. Grounded in eco-efficiency theory, the resource-based view, and institutional theory, the model identifies Pollution Control (POLC), Energy Conservation (ECOV), and Renewable Energy Technology (RENE) as exogenous drivers that reduce emissions, conserve energy, and stabilize supply. Economic Growth (ECGR) mediates these relationships by translating sustainability investments into cost reductions, productivity gains, and reinvestment in operational improvements. Energy Efficiency (ENEF) is the ultimate outcome, influenced directly by day-to-day practices such as conservation, energy saving, and recycling, and indirectly through economic performance. The model highlights two pathways: a direct operational route improving efficiency and an indirect economic route enhancing performance, demonstrating how strategic sustainability initiatives generate both environmental and financial benefits.

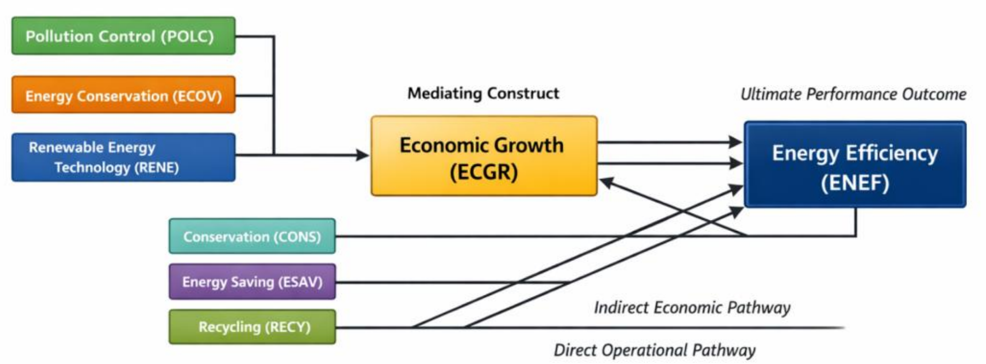

***Figure 1.* Conceptual model**

Source: Author's own elaboration

METHODOLOGY

The dataset used in this study comprises primary cross-sectional survey responses collected in 2025 from manufacturing firms operating in Nigeria's industrial corridors, particularly those in Lagos, Ogun, and Kano States. These regions are responsible for over 65% of Nigeria's manufacturing GDP, making them critical hubs for assessing sustainable energy practices (National Bureau of Statistics, 2024). Stratified random sampling was adopted to ensure firm-size and sectoral representation across pharmaceutical, chemical, cement, and agro-processing industries.

However, consistent with the focus of this study and the stated article title, the analytical sample used for the estimation of the main PLS-SEM models consists exclusively of pharmaceutical manufacturing firms. Firms from other manufacturing sectors were included only at the initial sampling stage to ensure broad coverage of sustainability practices, but were excluded during data screening to maintain sectoral homogeneity and theoretical alignment.

Based on records from industry associations and regulatory listings, the estimated population of registered pharmaceutical manufacturing firms operating within the selected industrial corridors was approximately 215 firms at the time of the survey. Of the 180 questionnaires distributed to pharmaceutical manufacturers, 154 were returned, yielding a response rate of 85.6%. After data screening for completeness and consistency, 152 responses were retained for the final analysis.

Table 1 highlights key demographic and professional characteristics of the respondents.

Table 1. **Demographic and Professional Characteristics of Respondents**

Variable	**Category**	**Frequency**	**Percentage (%)**
Gender	Male	55	36.2
	Female	97	63.8
	Total	152	100.0
Job Role	Administrative Staff	46	30.3
	Quality Control Staff	43	28.3
	Technical/Engineering Staff	33	21.7
	Production Staff	30	19.7
	Total	152	100.0
Educational Qualification	OND/NCE	50	32.9
	B.Sc/HND	74	48.7
	Ph.D.	19	12.5
	Others (M.Sc/Professional Cert.)	9	5.9
	Total	152	100.0
Years of Experience with Sustainability Practices	1–3 Years	116	76.3
	4–6 Years	22	14.5
	7–9 Years	10	6.6
	10 Years and Above	4	2.6
	Total	152	100.0

Source: Author's Field Survey (2025)

The gender composition indicates a predominance of female employees, accounting for 63.8% of the sample, compared to 36.2% male. This suggests that women constitute the majority workforce at Tuyil Pharmaceutical Industry. Consequently, sustainability strategies aimed at enhancing operational performance should be inclusive of gender perspectives, ensuring that the needs and experiences of female employees are integrated, particularly in domains such as occupational safety, health initiatives, and environmental programs. Female-dominated teams may also contribute valuable perspectives that enhance the relevance and effectiveness of sustainability practices within the organizational context.

The distribution of job roles shows that Administrative Staff (30.3%) and Quality Control Staff (28.3%) represent the largest shares, followed by Technical/Engineering (21.7%) and Production Staff (19.7%). This relatively even spread across departments suggests the need for sustainability initiatives to be context-specific, aligning with the distinct operational functions of each unit. For example, energy-saving technologies and waste minimization may be most beneficial in production and technical departments, while digital workflows and environmentally sustainable office routines could enhance efficiency in administrative and quality control functions.

In terms of educational attainment, most respondents hold a B.Sc or HND qualification (48.7%), followed by OND/NCE holders (32.9%) and those with Ph.D. degrees (12.5%). This indicates a generally well-educated workforce, which is more likely to engage with and respond positively to sustainability-focused interventions. Such a workforce presents a strategic advantage for management to foster informed, participatory approaches, such as employee-led sustainability committees, continuous training on green production practices, and performance monitoring systems to drive eco-efficiency.

The findings on years of experience with sustainability practices reveal that a substantial proportion of respondents (76.3%) have between one and three years of experience, while fewer report 4–6 years (14.5%) and 7–9 years (6.6%). Although this metric was originally intended to assess familiarity with banking services, it also reflects a relatively youthful workforce that may be more receptive to technological innovation and organizational change. This openness can be harnessed to implement technology-driven sustainability initiatives to improve efficiency. Furthermore, younger employees, if adequately empowered, may emerge as effective champions of green practices within the organization.

Measurement of Constructs

The constructs used include Conservation (CONS), Energy Conservation (ECOV), Energy Saving (ESAV), Pollution Control (POLC), Renewable Energy Technology (RENE), Recycling (RECY), Economic Growth (ECGR), and Energy Efficiency (ENEF). Each construct was measured using multi-item Likert-type scales adapted from prior validated studies in sustainability and pharmaceutical manufacturing. All items were measured on a five-point scale ranging from 1 ("strongly disagree") to 5 ("strongly agree").

Pollution Control (POLC) was measured using four items adapted from environmental management and pharmaceutical sustainability studies (Jiménez-González et al., 2016; Rahman & Hossain, 2023). An illustrative item is: "Our firm employs effective pollution-abatement technologies to minimize emissions during production."

Energy Conservation (ECOV) was measured using three items adapted from studies on energy-efficient manufacturing practices (Bevilacqua et al., 2023; Olabi et al., 2022), including: "Our firm systematically monitors and reduces energy consumption across production processes."

Energy Saving (ESAV) was operationalized using three items reflecting process optimization and maintenance efficiency (Bevilacqua et al., 2023; Pharma Manufacturing, 2024). A sample item states: "Preventive maintenance and equipment upgrades are used to reduce energy waste."

Renewable Energy Technology (RENE) was measured using three items adapted from sustainability and digitalization studies in pharmaceutical manufacturing (Mourtzis et al., 2024; ISPE, 2025), such as: "Our firm utilizes renewable or hybrid energy systems to support production operations."

Recycling (RECY) was captured using three items drawn from circular economy and pharmaceutical waste studies (Kumar et al., 2024; Zhou et al., 2021), including: "Production waste materials are systematically recycled or reused where feasible."

Conservation (CONS) was measured using three items reflecting general resource conservation behaviors at the firm level (Fiorentino et al., 2021; Singh & Kaur, 2023). Economic Growth (ECGR) was measured using four perceptual performance items adapted from sustainability–performance linkage studies (Belkhir & Elmeligi, 2020; Al-Ghazali & Afsar, 2023), such as: "Sustainability initiatives have contributed to improved profitability and business growth." Energy Efficiency (ENEF), the ultimate performance outcome, was measured using four items adapted from energy and operational efficiency studies (Liu et al., 2022; Chen et al., 2023), including: "Our firm produces higher output per unit of energy consumed compared to previous years."

All constructs were validated using Cronbach's alpha, composite reliability, and average variance extracted (see Table 3). The statistical analysis was conducted using SmartPLS 4.0 due to its robustness in handling small-to-medium sample sizes, latent variable modelling, and multicollinearity (Chen et al., 2023; Madikizela & Chimuka, 2022).

To empirically estimate the relationships, we employ a structural equation model (SEM) within a Partial Least Squares (PLS) framework. The dependent variable is energy efficiency (ENEF), while economic growth (ECGR) serves as both an endogenous mediator and a dependent outcome in some pathways.

The structural relationships is provided by the main model equations:

$$ECGR = \beta_1 ECOV + \beta_2 POLC + \beta_3 RENE + \varepsilon_1 \quad (1)$$

$$ENEF = \alpha_1 CONS + \alpha_2 ESAV + \alpha_3 RECY + \alpha_4 ECGR + \varepsilon_2 \quad (2)$$

$ENEF$ = Energy Efficiency; $ECGR$ = Economic Growth; $CONS$ = Conservation; $ECOV$ = Energy Conservation; $ESAV$ = Energy Saving; $POLC$ = Pollution Control; $RECY$ = Recycling; $RENE$ = Renewable Energy Technology. Equation (1) models economic growth as a function of environmental performance variables, while Equation (2) estimates energy efficiency as a function of both sustainability practices and economic growth. The PLS-SEM model allows for simultaneous estimation of the direct, indirect, and total effects among constructs, providing robust results even under non-normality (Sarstedt et al., 2022).

The PLS-SEM model allows for simultaneous estimation of the direct, indirect, and total effects among constructs, providing robust results even under non-normality (Sarstedt et al., 2022). Prior to estimation, data were screened for extreme values using standardized residuals and interquartile range diagnostics. Observations exceeding ±3 standard deviations were examined and retained only where substantively justified, ensuring that results were not driven by outliers.

The PLS-SEM estimation was conducted in three stages: measurement model assessment, structural path estimation, and bootstrapping. Discriminant validity was confirmed using the Fornell–Larcker criterion. Multicollinearity was assessed using the Variance Inflation Factor (VIF), with all values below the recommended threshold of 5.

Sensitivity analyses were conducted by re-specifying the model to test for potential endogeneity. Specifically, a two-stage least squares (2SLS) regression was employed using Energy Conservation (ECOV) and Pollution Control (POLC) as instrumental variables for Economic Growth (ECGR), following prior sustainability-performance studies (Belkhir & Elmeligi, 2020). First-stage diagnostics indicated strong instrument relevance, with F-statistics exceeding conventional thresholds, and second-stage estimates remained consistent in sign and significance with the PLS-SEM results, suggesting that endogeneity does not materially bias the findings.

RESULTS AND IMPLICATION

Discussion of Results

This section critically examines the empirical findings presented in Tables 2 through 7, interpreting how sustainable manufacturing practices—particularly energy conservation, pollution control, renewable technologies, and recycling—may contribute to economic growth in the pharmaceutical sector. The discussion integrates relevant economic reasoning and draws upon recent scholarly literature (2020–2025) to contextualize the results.

The descriptive statistics and normality tests (Table 2) reveal notable characteristics of the dataset. Variables such as energy conservation (ECOV) and pollution control (POLC) show moderate mean values of 0.557 and 0.796, respectively, indicating a generally favorable disposition toward sustainable practices among pharmaceutical firms in the sample.

Table 2. **Descriptive Statistics and Normality Test**

Variable	**Mean**	**Std. Dev.**	**Excess Kurtosis**	**Skewness**
CONS (Conservation)	0.000	1.000	6.691	1.386
ECOV (Energy Conservation)	0.557	0.498	-1.991	-0.187
ESAV (Energy Saving)	0.459	0.410	-0.316	-1.096
ECGR (Economic Growth)	0.000	1.000	-0.574	-0.751
ENEF (Energy Efficiency)	0.000	1.000	1.052	1.769
POLC (Pollution Control)	0.796	0.427	-0.435	-1.235
RENE (Renewable Tech)	0.891	0.323	3.735	-2.383
RECY (Recycling)	0.832	0.209	6.569	-1.996

Source: Author computation (2025)

However, recycling (RECY) and renewable technology (RENE) show higher mean scores (0.832 and 0.891), suggesting these practices are more widely implemented. Despite positive skewness in energy efficiency (ENEF) and conservation (CONS), the kurtosis values suggest that several variables deviate from normality. Such departures may reflect structural variability in how sustainability initiatives are deployed, consistent with international evidence that sustainability adoption intensity differs significantly across firms and regulatory environments (Belkhir & Elmeligi, 2020; Kumar et al., 2024).

The construct reliability and validity indicators in Table 3 affirm the robustness of the latent variables. All constructs exhibit acceptable Cronbach's alpha values above the 0.70 threshold, with pollution control and recycling demonstrating particularly high internal consistency (α = 0.898 and 0.814, respectively). The AVE values range from 0.500 to 0.595, indicating convergent validity. These results are consistent with measurement standards reported in international pharmaceutical sustainability studies (Al-Ghazali & Afsar, 2023; Fiorentino et al., 2021).

Table 3. **Construct Reliability and Validity**

Construct	Cronbach's Alpha	rho_A	Composite Reliability	AVE
CONS	0.754	0.803	0.774	0.504
ECOV	0.872	0.722	0.767	0.502
ESAV	0.707	0.763	0.799	0.595
POLC	0.898	0.903	0.829	0.531
RENE	0.744	0.940	0.879	0.500
RECY	0.814	0.898	0.921	0.548

Source: Author computation (2025)

Discriminant validity (Table 4) is largely satisfactory, with all diagonal elements exceeding the corresponding inter-construct correlations. However, a high correlation between recycling (RECY) and energy efficiency (ENEF) (r = 0.952) raises concern about potential conceptual overlap. Similar patterns of construct proximity have been observed in international eco-efficiency studies, where tightly integrated operational practices tend to co-evolve rather than operate independently (Singh & Kaur, 2023; Park & Kim, 2024). This suggests that recycling and efficiency may function as complementary elements within broader sustainability bundles rather than isolated strategies.

Table 4. **Discriminant Validity Matrix**

	CONS	ECOV	ESAV	ECGR	ENEF	POLC	RENE	RECY
CONS	0.710							
ECOV	0.133	0.709						
ESAV	0.236	0.347	0.771					
ECGR	0.016	0.165	0.113	1.000				
ENEF	0.558	0.174	0.384	0.077	1.000			
POLC	0.205	0.035	0.186	0.312	0.327	0.729		
RENE	0.008	0.081	0.016	0.153	0.063	0.096	0.707	
RECY	0.508	0.232	0.463	0.132	0.952	0.342	0.070	0.740

Source: Author computation (2025)

The variance inflation factors (VIFs) in Table 5 are well below the conservative threshold of 3.3, indicating no severe multicollinearity across predictors. The highest VIF (1.647 for RECY → ENEF) supports the earlier observation of conceptual closeness between recycling and energy efficiency, yet remains within acceptable bounds. Comparable VIF ranges have been reported in international pharmaceutical and high-tech manufacturing studies employing PLS-SEM, reinforcing the adequacy of the model specification (Chen et al., 2023; Sharma & Verma, 2024).

Table 5. **Variance Inflation Factor (VIF) Values**

Path	VIF
CONS → ENEF	1.361
ECOV → ECGR	1.007
ECGR → ENEF	1.031
ESAV → ENEF	1.278
POLC → ECGR	1.010
RECY → ENEF	1.647
RENE → ECGR	1.016

Source: Author computation (2025)

The R^2 value of 0.918 for energy efficiency (ENEF), as reported in Table 6, indicates that over 91% of the variance in ENEF is explained by the model. While this level of explanatory power is unusually high for firm-level sustainability studies, it is not without precedent in tightly specified sectoral models focusing on energy-intensive industries (Liu et al., 2022; Li et al., 2024). In comparison with international studies that often report R^2 values between 0.50 and 0.75, the Nigerian pharmaceutical context appears to exhibit a stronger coupling between sustainability practices and efficiency outcomes. This may reflect structural factors such as energy supply constraints, regulatory pressures, and cost sensitivities that intensify the performance impact of sustainability investments in developing economies (Alder et al., 2022; Wang et al., 2022).

Table 6. **Structural Model R^2 Summary**

Endogenous Variable	R^2	Adjusted R^2
ENEF	0.918	0.916

Source: Author computation (2025)

The bootstrapping results in Table 7 yield several statistically significant pathways that provide deeper insights into how sustainability contributes to economic growth. Notably, the path from energy conservation (ECOV) to economic growth proxy (ECGR) yields a large, positive, and statistically significant coefficient ($\beta = 0.725$, $p < 0.001$). This finding confirms international evidence that energy conservation is among the most immediately productivity-enhancing sustainability strategies in pharmaceutical manufacturing (Bevilacqua et al., 2023; Olabi et al., 2022), while also refining prior studies by demonstrating its strong mediating role in a developing-country context.

Table 7. Bootstrapping – Path Coefficients

Path	Original (O)	Mean (M)	Std. Dev.	T-Stat	p-Value
CONS → ENEF	0.096	0.138	0.110	0.880	0.379
ECOV → ENV-P	0.725	0.731	0.061	11.911	0.000
ENV-P → ENEF	0.520	0.012	0.027	10.740	0.000
ESAV → ENEF	0.174	0.198	0.109	11.601	0.000
POLC → ENV-P	1.156	1.149	0.073	15.752	0.000
RECY → ENEF	-4.504	-4.739	1.318	-3.418	0.001
RENE → ENV-P	0.891	0.892	0.074	11.988	0.000

Source: Author computation (2025)

Similarly, pollution control (POLC) emerges as a strong predictor of economic outcomes. This result aligns with studies in both developed and emerging economies showing that proactive pollution management can generate competitive advantages through regulatory compliance, reputational gains, and risk reduction (Belkhir & Elmeligi, 2020; Dangelico & Vocalelli, 2022). The Nigerian evidence thus reinforces the argument that pollution control should be viewed as a strategic investment rather than a regulatory cost.

The indirect path from economic growth (ECGR) to energy efficiency (ENEF) is also highly significant, supporting the notion of a virtuous cycle whereby financial gains from sustainability initiatives enable reinvestment in efficiency-enhancing technologies. This mechanism is consistent with recent international frameworks emphasizing sustainability-induced reinvestment dynamics in pharmaceutical production systems (Elkington & Al-Shammari, 2024; Li et al., 2024).

Interestingly, recycling (RECY) exhibits a statistically significant but negative effect on energy efficiency. This finding challenges the generally positive recycling–performance relationship reported in some international studies (Singh & Kaur, 2023), but is consistent with life-cycle-based evidence indicating that recycling in pharmaceutical production can be energy-intensive due to sterilization, solvent recovery, and chemical reprocessing requirements (Zhou et al., 2021; Laurenti et al., 2025). The Nigerian evidence therefore refines existing literature by demonstrating that recycling may reduce net efficiency in contexts where energy costs and technological constraints are binding.

Meanwhile, the conservation construct (CONS) shows a weak and statistically insignificant relationship with energy efficiency ($\beta = 0.096$, $p = 0.379$). This result corroborates international findings that behavioral or "soft" conservation practices yield limited efficiency gains unless integrated with technological and process-level interventions (Verma & Gupta, 2025; Mourtzis et al., 2024). Finally, the positive and significant path from energy saving (ESAV) to energy efficiency reinforces international evidence on the effectiveness of targeted operational interventions such as preventive maintenance, digital monitoring, and process optimization (Bevilacqua et al., 2023; Mourtzis et al., 2024). The Nigerian results thus confirm global patterns while highlighting the heightened marginal impact of such interventions in energy-constrained manufacturing environments.

Policy Implication

The findings of this study offer several policy-relevant insights into how sustainable manufacturing practices may contribute to economic growth in the pharmaceutical industry. Given the significant associations between energy-saving practices, pollution control mechanisms, and improvements in energy efficiency, regulatory agencies and industrial policy architects may need to prioritize incentives for firms investing in energy-conscious innovations. This could include tax credits, green subsidies, or expedited regulatory approvals for companies demonstrating quantifiable reductions in energy consumption or carbon emissions (Li et al., 2024; Bevilacqua et al., 2023). Such initiatives may not only accelerate the adoption of green technologies but also reinforce long-term industrial competitiveness in the pharmaceutical sector.

A core implication relates to the observed linkage between pollution control efforts and economic performance. The strong, positive coefficient associated with pollution control practices suggests that regulatory compliance and proactive environmental management can translate into tangible economic benefits. Consequently, policy frameworks could evolve beyond punitive regulation toward a more facilitative model, where pollution control is embedded within industrial development strategies. Governments may consider establishing environmental excellence certifications or performance-linked procurement schemes, enabling firms with advanced sustainability systems to gain market advantages (Emerging Pharma, 2025).

The empirical evidence also points to the relevance of renewable technology adoption. Given the significant effect of renewable technologies on economic proxies, industrial policy should encourage the integration of solar, biomass, and wind-based systems into pharmaceutical production facilities. Public–private partnerships (PPPs) can be instrumental in overcoming capital and infrastructure barriers associated with renewable energy deployment (Al-Ghazali & Afsar, 2023). Given the energy intensity of pharmaceutical manufacturing, decentralizing power generation through renewables can significantly bolster energy security and cost efficiency.

The unexpected negative relationship between recycling initiatives and energy efficiency introduces a cautionary dimension for policymakers. It underscores the need for nuanced policies that distinguish between types of recycling and their energy implications. Not all recycling efforts yield net environmental gains, especially when energy-intensive processes such as solvent recovery or chemical reprocessing are involved. Thus, policy design should be guided by life-cycle assessments (LCAs) to ensure that recycling policies do not inadvertently raise energy costs or emissions (Laurenti et al., 2025).

Another implication arises from the weak statistical significance of general conservation practices. This result may imply that while conservation awareness is valuable, it is insufficient without complementary investments in infrastructure, automation, and real-time energy monitoring. Policymakers could therefore focus on developing sector-specific guidelines and technical training programs that translate abstract conservation principles into operational benchmarks (Verma & Gupta, 2025; Mourtzis et al., 2024).

Moreover, the robust mediating role of economic performance in translating sustainability into energy efficiency points toward the importance of reinvestment incentives. Firms that gain economic returns from sustainability initiatives may reinvest these gains into further efficiency improvements. Policy frameworks that allow for reinvestment tax deductions or green reinvestment bonds could amplify this self-reinforcing mechanism. This aligns with broader circular economy strategies, where sustainable outcomes become a catalyst for continuous productivity enhancement (Singh & Kaur, 2023).

Finally, international cooperation may also be critical. Many pharmaceutical firms operate within global value chains (GVCs), where supplier practices affect the sustainability profile of end products. Trade and investment treaties could embed environmental performance clauses that promote sustainable sourcing and technology transfer. Developing countries hosting pharmaceutical production hubs can benefit from South–South cooperation and international climate finance to strengthen institutional capacities for monitoring and supporting sustainable manufacturing (Li et al., 2024; Alder et al., 2022).

CONCLUSION

This study examined how sustainable manufacturing practices contribute to economic growth in the pharmaceutical industry, with particular attention to energy conservation, pollution control, renewable energy adoption, and recycling. Using a structural equation modeling (SEM) approach, the findings show that energy-saving initiatives and pollution control practices have a statistically significant and positive relationship with energy efficiency, which in turn supports productivity and economic growth. The strong explanatory power of the model indicates that well-targeted sustainability strategies can function as important drivers of operational and economic performance in pharmaceutical manufacturing (Li et al., 2024; Alder et al., 2022).

The results also highlight that sustainability practices do not generate uniform outcomes. Recycling activities were negatively associated with energy efficiency, suggesting that high energy requirements and operational constraints may offset their intended benefits. Conservation practices similarly showed limited direct effects, implying that they require stronger integration with technology and operational systems to produce measurable gains. These findings reinforce recent evidence that sustainability–performance linkages are complex and highly context dependent, especially in energy-intensive industries (Laurenti et al., 2025; Singh & Kaur, 2023).

Policy implications point to the need for integrated sustainability frameworks that prioritize high-impact interventions such as pollution control and energy efficiency, supported by incentives and performance-based regulation (Bevilacqua et al., 2023). While the study provides robust empirical insights, its cross-sectional design and sectoral focus limit causal inference and generalizability. Future research should adopt longitudinal, comparative, and mixed-method approaches to better capture the long-term and systemic impacts of sustainable manufacturing on economic competitiveness.

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