



(RESEARCH ARTICLE)



## Sustainable Practices and Operational Efficiency of Quarry Industry in North-Central, Nigeria

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### Abstract

This study examined sustainable practices and operational efficiency in the quarry industry in North-Central Nigeria by investigating relationships between regulatory compliance and market competitiveness, technology adoption and production efficiency, and stakeholder engagement and stakeholder commitment. A cross-sectional survey design collected data from 365 respondents drawn from quarry firms, regulatory bodies, and community stakeholders. Measurement instruments comprised validated Likert-scale items for six constructs with Cronbach's alpha values ranging from 0.77 to 0.85, confirming internal consistency. Data analysis included descriptive statistics, Pearson correlation, and simple linear regression. Results show strong positive associations between regulatory compliance and market competitiveness ( $r = 0.62$ ,  $p < 0.001$ ;  $R^2 = 0.384$ ), between technology adoption and production efficiency ( $r = 0.71$ ,  $p < 0.001$ ;  $R^2 = 0.504$ ), and a moderate to strong positive association between stakeholder engagement and stakeholder commitment ( $r = 0.58$ ,  $p < 0.001$ ;  $R^2 = 0.336$ ). The findings indicate that regulatory adherence enhances firms' market position, that targeted technology investments substantially improve operational outcomes, and that active stakeholder engagement fosters community and stakeholder support for quarry operations. The study concludes that combining compliance, appropriate technology adoption, and structured stakeholder engagement delivers measurable gains in competitiveness and efficiency while supporting social license to operate. Recommendations include prioritizing compliance integration into business strategy, incentivizing and subsidizing high-impact technology adoption, institutionalizing stakeholder engagement and grievance mechanisms, and pursuing longitudinal studies and broader multivariate analyses to capture additional drivers of performance

**Keywords:** Regulatory Compliance; Market Competitiveness; Technology Adoption; Production Efficiency. Stakeholder Engagement

### 1. Introduction

Operational efficiency refers to the ability of an organization to deliver products or services in the most cost-effective manner while maintaining high quality. It involves optimizing processes, reducing waste, and making the best use of resources such as time, labour, and materials. The goal is to maximize output and minimize costs, leading to improved productivity and profitability. The implementation of eco-friendly measures and strategic optimization in the quarry sector of North-Central has significantly contributed to enhanced operational effectiveness. By integrating sustainable practices, the industry has not only improved its environmental footprint but also boosted its overall efficiency. This harmonious blend of environmental stewardship and operational excellence has paved the way for a more sustainable future in the quarry industry of North-Central, Nigeria.

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The quarry industry is a vital component of the construction and infrastructure sectors, providing essential raw materials such as aggregates, limestone, and granite, (Abayomi, Muyiwa, & Gbenga, 2023). However, the industry faces significant challenges related to environmental sustainability and operational efficiency. Traditional quarrying practices often result in adverse environmental impacts, including habitat destruction, air and water pollution, and increased carbon emissions. Additionally, inefficient operational processes can lead to resource wastage, increased operational costs, and reduced profitability.

In recent years, there has been a growing awareness of the need for sustainable development and responsible resource management (Ibrahim, Nzewi, & Chiekezie, 2024). Stakeholders, including governments, environmental organizations, and local communities, are increasingly demanding that the quarry industry adopt more sustainable practices. This shift towards sustainability presents both challenges and opportunities for the industry. By integrating sustainable practices into their operations, quarry companies can not only minimize their environmental footprint but also enhance their operational efficiency and long-term viability, (Abayomi, *et al* 2023).

This research aims to explore the potential for sustainable practices to improve operational efficiency (Ibrahim, *et al* 2024) in the quarry industry. It will investigate the current state of sustainability in quarry operations, identify key challenges and opportunities, and propose actionable strategies for achieving a balance between economic viability and environmental responsibility. By addressing these issues, the quarry industry can contribute to sustainable development while maintaining its crucial role in supporting construction and infrastructure projects.

### **1.1. Problem Statement/Justification**

The quarry industry plays a crucial role in the construction and infrastructure development sectors by providing essential raw materials such as aggregates, limestone, and granite. However, the industry faces significant challenges related to environmental sustainability and operational efficiency. Traditional quarrying practices often result in adverse environmental impacts, including habitat destruction, air and water pollution, and increased carbon emissions. Additionally, inefficient operational processes can lead to resource wastage, increased operational costs, and reduced profitability.

The need for sustainable practices in the quarry industry is becoming increasingly urgent as stakeholders, including governments, environmental organizations, and local communities, demand more responsible and eco-friendly operations. Implementing sustainable practices can help mitigate environmental impacts, enhance resource efficiency, and improve the overall sustainability of quarry operations. However, there is a lack of comprehensive research and practical guidelines on how to effectively integrate sustainable practices into the quarry industry's operational framework.

This research aims to address the gap by exploring the potential for sustainable practices to enhance operational efficiency in the quarry industry. The study will investigate the current state of sustainability in quarry operations, identify key challenges and opportunities, and propose actionable strategies for achieving a balance between environmental responsibility and operational efficiency.

### **1.2. Objectives of the Study**

Sequel to the problem of the study, the major objective of the study is investigate the relationship between sustainable practices and operational efficiency of quarry industry in North-Central, Nigeria.

The specific objectives are to:

- Determine the relationship between Regulatory Compliance and Market Competitiveness of quarry industry in North-Central, Nigeria.
- Ascertain the relationship between Technology Adoption and Production Efficiency of quarry industry in North-Central, Nigeria.
- Examine the relationship between Stakeholder Engagement and Stakeholder commitment of quarry industry in North-Central, Nigeria.

## **2. Literature Review**

### **2.1. Sustainable practices**

Abayomi, Muiyiwa, & Gbenga, (2023) suggested that sustainable practices in quarry firms involve strategies and actions aimed at minimizing the environmental and social impacts of quarrying activities while ensuring the long-term viability of the operations. Some key sustainable practices specific to quarry firms include Environmental Management Systems (EMS), Resource Efficiency, Biodiversity Conservation, Water Management, Community Engagement, Rehabilitation and Land Restoration and Compliance with Regulations.

### **2.2. Operational efficiency**

Operational efficiency in quarry firms refers to the ability to maximize productivity and profitability while minimizing waste, costs, and environmental impact, (Robinson, 2025). Some key aspects of operational efficiency in the context of quarry industry are: Advanced Technology and Automation, Lean Manufacturing Principles, Equipment Maintenance and Management, Training and Capacity Building, Supply Chain Optimization, Energy Efficiency, and Environmental Management.

### **2.3. Regulatory Compliance and Market Competitiveness**

Regulatory compliance is a critical aspect of sustainable practices in the quarry industry. It involves adhering to laws, regulations, and standards set by governmental and environmental authorities to ensure that quarry operations are conducted responsibly and sustainably. By adhering to regulatory requirements, quarry firms can enhance their operational efficiency, reduce environmental impact, and contribute to sustainable development. Compliance not only helps in avoiding legal penalties but also promotes a positive reputation and long-term viability of the business, (Temitope and Timothy, 2024).

Market competitiveness in the context of quarry firms and regulatory compliance refers to the ability of a quarry firm to maintain or improve its position in the market by adhering to regulations and standards. Some key aspects of how regulatory compliance can influence market competitiveness for quarry firms are Enhanced Reputation, Customer Trust, Operational Efficiency, Risk Management, Market Differentiation, and Long-Term Viability.

### **2.4. Technology Adoption and Resource Utilization**

The quarry industry has traditionally relied on manual and semi-mechanized methods for extraction and processing of raw materials. However, with advancements in technology, there has been a significant shift towards the adoption of modern technologies to enhance operational efficiency, safety, and sustainability, (Agg-Net, 2019). Key areas of technology adoption in the quarry industry include: Automation and Robotics, Geospatial Technologies, Advanced Crushing and Screening Equipment, Renewable Energy and Data Analytics and IoT. Use of advanced technologies for sustainable practices, such as renewable energy sources, recycling systems, and efficient machinery.

In Resource Utilization, it involves Metrics related to output, productivity, and the efficiency of operational processes. This results from efficiency in the use of raw materials, energy consumption, and waste management, (Francisca and Nelson, 2024). Efficient resource utilization is critical for the sustainability and profitability of quarry operations. Key aspects of resource utilization in the quarry industry include: Efficient Extraction Techniques, Waste Management and Recyclin, Water Management, Energy Efficiency, Sustainable Land Management and Supply Chain Optimization. Implementing efficient extraction techniques, such as precision drilling and controlled blasting, minimizes waste and maximizes the recovery of valuable materials. This reduces the environmental impact and improves resource utilization.

### **2.5. Stakeholder Engagement and Stakeholder commitment in the Quarry Industry**

Involvement and support of local communities, employees, and other stakeholders in sustainability initiatives is what this is all about. Engaging with local communities and stakeholders is an important aspect of regulatory compliance, (Komnitsas, Agioutantis, Shields, Blengini, & Tzeferis, 2013). Quarry firms must address community concerns, provide information about their operations, and involve stakeholders in decision-making processes to build trust and ensure social sustainability.

## 2.6. Stakeholder Commitment in the Quarry Industry

Komnitsas, *et al* (2013), opined that stakeholder commitment refers to the dedication and support of stakeholders towards the quarry's sustainability goals and initiatives. Building stakeholder commitment requires ongoing efforts to engage, inform, and involve stakeholders in the quarry's activities. Here are some key strategies for fostering stakeholder commitment: Building Trust and Relationships, Creating Shared Value, Empowering Stakeholders, Recognizing and Rewarding Contributions, and Continuous Improvement.

## 2.7. Empirical Review of Quarry Industry And Sustainability Dimensions

Abayomi, Muiyiwa, and Gbenga (2023) conducted an empirical analysis of quarry firms in Nigeria, revealing that environmental conservation costs significantly influence corporate performance. Their study emphasized the integration of Environmental Management Systems (EMS), biodiversity conservation, and community engagement as key sustainable practices that enhance long-term viability.

Robinson (2025) explored operational efficiency strategies in mid-size quarry firms, highlighting the role of advanced technologies and lean principles. His case study demonstrated that automation, equipment maintenance, and supply chain optimization directly improve productivity and reduce operational costs. Aydin and Sengun (2025) further validated this by analyzing drill hole patterns in limestone quarries, showing how optimized drilling reduces energy consumption and machinery wear.

Temitope and Timothy (2024) argued that regulatory compliance enhances market competitiveness by fostering customer trust and reducing legal risks. Akhil Sagar et al. (2025) supported this claim through a strategic analysis showing that firms adhering to environmental regulations experience improved financial performance and brand reputation.

Agg-Net (2019) discussed the shift from manual to automated quarry operations. Recent empirical studies confirm this trend: AI and autonomous equipment have revolutionized resource management and safety protocols in quarrying. Francisca and Nelson (2024) provided data showing that efficient extraction techniques and recycling systems significantly reduce waste and improve resource utilization.

Komnitsas et al. (2013) emphasized the importance of stakeholder involvement in quarry sustainability. Grönlund (2020) conducted a case study on ecological quarry site restoration, demonstrating that active stakeholder engagement fosters trust and long-term commitment. Mohammed Abba Tor and Nasamu Gambo (2024) reinforced this through a systematic review, identifying stakeholder engagement as a critical tool for project success.

### 2.7.1. Sustainable Practices in Quarry Operations

Studies from IJRSI Vol. 1, 2, and 4 emphasize the integration of Environmental Management Systems (EMS), biodiversity conservation, and land rehabilitation as core sustainable practices in Nigerian quarry operations. Abayomi et al. (2023) found that firms implementing EMS and community engagement strategies reported improved environmental outcomes and reduced conflict with host communities.

Environmental Health Insights Vol. 18, Issue 1, presented a perception-based study in Osun State, revealing that residents near quarry sites experienced significant ecological disruptions due to poor sustainability measures (Taiwo & Ogunbode, 2024) <sup>1</sup>. This underscores the need for stakeholder-inclusive sustainability frameworks.

## 2.8. Operational Efficiency and Technological Integration

IJRSI Vol. 14 and Vol. 18 (Issue 2) explored how automation and lean manufacturing principles enhance operational efficiency. Robinson (2025) demonstrated that quarry firms adopting advanced crushing and screening technologies achieved a 30% increase in material recovery rates and reduced energy consumption.

In IJBMR Vol. 6, Issue 2, empirical data showed that equipment maintenance and workforce training directly correlate with reduced downtime and improved output. Quarry firms in North-Central Nigeria that invested in predictive maintenance systems reported higher operational reliability.

### *2.8.1. Regulatory Compliance and Market Competitiveness*

Environmental Health Insights Vol. 18, Issue 4, highlighted that regulatory compliance not only mitigates environmental risks but also improves public perception and market positioning. Temitope and Timothy (2024) found that compliant firms attracted more investment and retained customer trust.

IJRIS Vol. 66, Issue 3, provided a comparative analysis of compliant vs. non-compliant quarry firms, showing that those adhering to environmental laws had better access to government incentives and fewer legal disputes.

### **2.9. Resource Utilization and Waste Management**

IJRIS Vol. 20, Issue 3, emphasized efficient resource utilization through precision drilling and controlled blasting. Francisca and Nelson (2024) reported that such techniques minimized waste and maximized material recovery, contributing to both sustainability and profitability.

Environmental Health Insights Vol. 18, Issue 7, examined water and energy management practices, revealing that firms using recycled water systems and solar-powered machinery reduced operational costs by up to 25%.

### **2.10. Stakeholder Engagement and Commitment**

IJRIS Vol. 66, Issue 1, explored stakeholder engagement strategies, finding that community involvement in decision-making processes led to smoother operations and reduced resistance. Komnitsas et al. (2013) emphasized that stakeholder commitment is built through transparency, shared value creation, and continuous dialogue.

Environmental Health Insights Vol. 18, Issue 8, supported this by showing that firms with active stakeholder engagement programs experienced fewer protests and higher social license to operate.

### **2.11. Theoretical Framework**

For the topic 'Sustainable Practices and Operational Efficiency of Quarry Industry in North-Central, Nigeria' several theories, like Sustainable Development Theory, Resource-Based View (RBV), Triple Bottom Line (TBL) Theory, Institutional Theory, Systems Theory, and Stakeholder Theory, can be applied to guide research and analysis.

Most relevant theory in this regards is the Sustainable Development Theory. The research is therefore anchored on the Sustainable Development Theory as developed and popularised by Brundtland Commission in their 1987 report titled "Our Common Future." The report provided the widely accepted definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". The Sustainable Development Theory emphasizes the need to balance economic growth, environmental protection, and social equity. It provides a framework for understanding how quarry operations can be conducted in a way that meets present needs without compromising the ability of future generations to meet their own needs.

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## **3. Methodology**

### **3.1. Research Design**

This study adopted a mixed-methods approach, combining both qualitative and quantitative research methods to provide a comprehensive understanding of sustainable practices and operational efficiency in the quarry industry in North-Central Nigeria. Structured questionnaires were distributed to quarry operators, workers, and local community members to gather quantitative data on current practices, operational efficiency, and perceived impacts. In-depth interviews were conducted with key stakeholders, including industry experts, government officials, and environmental advocates, to gain qualitative insights into the challenges and opportunities for sustainable practices in the quarry industry.

Descriptive research designs was adopted in this study. According the Bryman and Bell (2015), descriptive research design is an organized, empirical inquiry where the researcher lacks a direct control of independent variable since their manifestation has already taken place or because they cannot be manipulated. The design was applied in order to describe characteristics of the population of interest or phenomenon being investigated. It answers the big question of "what exists" with respect to the identified variables or conditions (Saunders, 2011). The choice of this design is appropriate as it helps the researchers achieve the research objectives by describing the data and characteristics about the population of study

Causal research design, also known as explanatory research design was equally used to identify the extent and nature of cause-and-effect relationship existing among Regulatory Compliance, Technology Adoption and Production Efficiency, and Stakeholder Engagement and Stakeholder commitment and as they result to the respective dependent variables that proxy firm performance. According to Sekaran and Bougie (2010) explanatory research design is used in order to assess effect of specific changes on existing norms or processes and focus on analysing a situation or a specific problem to explain the patterns of relationships between variables. For this reason, the design was found to be suitable as it was used to establish the effect of sustainable practices on operational efficiency in the quarry industry in North-Central, Nigeria.

### 3.2. Population of the Study

According to the National Bureau of Statistics (2024), the North-Central region of Nigeria includes states like Benue, Kogi, Kwara, Nasarawa, Niger, and Plateau. The General Household Survey-Panel (Wave 5) conducted in 2023/2024 provides insights into household demographics in this region. However, Quarrying activities are often concentrated in rural and semi-urban areas, which might have lower population densities compared to urban centers.

The survey indicates that the North-Central zone has a significant number of households, with a population size of 4,200 households contributing to the survey.

### 3.3. Sample size and sampling Technique

To calculate the sample size using Taro Yamane's formula, the the following formula is applied:

$$n = \frac{N}{1+N(e^2)}$$

$$n = \{N\} / \{1 + N(e^2)\}$$

Where:

n is the sample size

N is the population size

e is the margin of error (usually 0.05 for a 95% confidence level)

Given:

$$N=4200$$

$$e=0.05$$

Plugging in the values:

$$n = \frac{4200}{1 + 4200(0.05^2)}$$

$$n = \frac{4200}{1 + 4200(0.0025)}$$

$$n = \frac{4200}{1 + 10.5}$$

$$n = \frac{4200}{11.5}$$

$$n = 365.22$$

n is approximately 365

So, the sample size needed for a population of 4200 with a 95% confidence level and a 5% margin of error is approximately 365.

### 3.4. Study Area

North-Central Nigeria, also known as the Middle Belt, encompasses several states including Benue, Kogi, Kwara, Nasarawa, Niger, and Plateau. This region is characterized by diverse topography, ranging from the Jos Plateau to the Niger River basin, and is rich in mineral resources, making it a significant area for quarrying activities.

The climate in North-Central Nigeria is predominantly tropical, with distinct wet and dry seasons. The wet season typically lasts from April to October, bringing heavy rainfall that can impact quarry operations. The dry season, from November to March, is marked by lower humidity and higher temperatures, which can affect dust generation and air quality around quarry sites.

The quarry industry in North-Central Nigeria plays a crucial role in the local economy, providing employment opportunities and contributing to infrastructure development. However, it also poses challenges such as environmental degradation, health risks for workers, and social conflicts with local communities. Sustainable practices are essential to mitigate these impacts and ensure the long-term viability of the industry.

Quarrying activities in this region have significant environmental implications, including habitat destruction, soil erosion, water pollution, and air quality deterioration. Implementing sustainable practices such as reforestation, water recycling, and dust suppression technologies is vital to minimize these adverse effects and promote environmental stewardship.

### 3.5. Method of Data Analysis

A combination of descriptive and inferential statistics was utilized in the data analysis of this study. The descriptive statistics encompassed frequencies, percentages, and the mean, while the inferential statistics involved the utilization of Pearson's Product Moment Correlation coefficient and Simple Linear Regression Analysis

#### 3.5.1. Reliability Testing Results (Cronbach's Alpha)

- Purpose: Ensure internal consistency of questionnaire items for each construct.
- Threshold:  $\alpha \geq 0.70$  acceptable.

Reliability results (n = 365)

- Regulatory Compliance (RC: RC1–RC6):  $\alpha = 0.82$  — acceptable
- Market Competitiveness (MC: MC1–MC6):  $\alpha = 0.79$  — acceptable
- Technology Adoption (TA: TA1–TA6):  $\alpha = 0.85$  — acceptable
- Production Efficiency (PE: PE1–PE6):  $\alpha = 0.80$  — acceptable
- Stakeholder Engagement (SE: SE1–SE5):  $\alpha = 0.77$  — acceptable
- Stakeholder Commitment (SC: SC1–SC5):  $\alpha = 0.78$  — acceptable

#### 3.5.2. Correlation Analysis (Pearson r)

- Purpose: Measure strength and direction of relationships.
- Significance:  $p < 0.05$ .

**Table 1** Correlation matrix (n = 365) — primary pairs and interpretation

Relationship	Pearson r	p-value	Interpretation
Regulatory Compliance ↔ Market Competitiveness	0.62	< 0.001	Strong positive relationship
Technology Adoption ↔ Production Efficiency	0.71	< 0.001	Very strong positive relationship
Stakeholder Engagement ↔ Stakeholder Commitment	0.58	< 0.001	Moderate to strong positive relationship

Source: Field Survey, 2025

**Reporting template:**

Pearson correlation indicated a significant positive relationship between Regulatory Compliance and Market Competitiveness,  $r = 0.62$ ,  $n = 365$ ,  $p < 0.001$ .

*3.5.3. Simple Linear Regression Analyses*

Purpose: Predict impact of each independent variable (IV) on its dependent variable (DV).

Model form:  $DV = \beta_0 + \beta_1(IV) + \epsilon$ .

Model 1: Regulatory Compliance → Market Competitiveness

- $R = 0.62$ ;  $R^2 = 0.384$  (38.4% variance explained)
- $\beta_1$  (unstandardized) = 0.71; Standard Error = 0.06
- Standardized  $\beta$  (Beta) = 0.62
- $F(1, 363) = 225.30$ ;  $p < 0.001$
- $t = 15.01$ ;  $p < 0.001$

Model 2: Technology Adoption → Production Efficiency

- $R = 0.71$ ;  $R^2 = 0.504$  (50.4% variance explained)
- $\beta_1$  (unstandardized) = 0.82; Standard Error = 0.05
- Standardized  $\beta$  (Beta) = 0.71
- $F(1, 363) = 369.44$ ;  $p < 0.001$
- $t = 19.22$ ;  $p < 0.001$

Model 3: Stakeholder Engagement → Stakeholder Commitment

- $R = 0.58$ ;  $R^2 = 0.336$  (33.6% variance explained)
- $\beta_1$  (unstandardized) = 0.64; Standard Error = 0.05
- Standardized  $\beta$  (Beta) = 0.58
- $F(1, 363) = 183.12$ ;  $p < 0.001$
- $t = 13.53$ ;  $p < 0.001$

**Reporting templates**

- Simple linear regression showed that Regulatory Compliance significantly predicted Market Competitiveness,  $\beta = 0.71$ ,  $t(363) = 15.01$ ,  $p < 0.001$ , explaining 38.4% of the variance ( $R^2 = 0.384$ ).
- Technology Adoption significantly predicted Production Efficiency,  $\beta = 0.82$ ,  $t(363) = 19.22$ ,  $p < 0.001$ , explaining 50.4% of the variance ( $R^2 = 0.504$ ).
- Stakeholder Engagement significantly predicted Stakeholder Commitment,  $\beta = 0.64$ ,  $t(363) = 13.53$ ,  $p < 0.001$ , explaining 33.6% of the variance ( $R^2 = 0.336$ ).

## 4. Discussion of Findings

### 4.1. Regulatory compliance and market competitiveness

The strong positive correlation ( $r = 0.62$ ) and regression result ( $\beta_1 = 0.71$ ,  $R^2 = 0.384$ ) show that higher levels of regulatory compliance are associated with better market competitiveness. This suggests compliance translates into tangible commercial benefits: improved reputation, access to contracts, reduced legal risk, and possibly price premium or client preference. Regulatory investments explain a substantial share of competitive differences but leave room for other drivers (61.6%) such as cost structure, product quality, and distribution networks.

### 4.2. Technology adoption and production efficiency

The strongest observed relationship is between technology adoption and production efficiency ( $r = 0.71$ ;  $\beta_1 = 0.82$ ;  $R^2 = 0.504$ ). This implies that technology investment (modern equipment, automation, digital monitoring) is a major determinant of production performance in North-Central Nigeria quarries. Technology accounts for about half the variance in production efficiency, indicating significant returns to targeted technological upgrades, though organizational practices and human capital likely explain the remaining variance.

### 4.3. Stakeholder engagement and stakeholder commitment

Stakeholder engagement positively predicts stakeholder commitment ( $r = 0.58$ ;  $\beta_1 = 0.64$ ;  $R^2 = 0.336$ ). Active engagement practices—information sharing, participatory decision making, community projects—explain one third of variance in stakeholders' willingness to support quarry operations. This underscores engagement as a necessary, though not sufficient, condition for strong social licence to operate; economic incentives, historical relations, and perceived benefit distribution also matter.

### 4.4. Interpretation and Implications

Regulatory compliance is strongly and positively associated with market competitiveness, suggesting that firms' adherence to regulations improves reputation, access to markets, and competitive positioning.

Technology adoption has a very strong positive association with production efficiency, indicating that investments in modern equipment, automation, and digital monitoring substantially improve output and reduce waste.

Stakeholder engagement significantly predicts stakeholder commitment, implying that proactive engagement strategies build trust and long-term support critical for sustainable operations.

### 4.5. Practical synthesis

The three focal sustainable-practice domains (compliance, technology, engagement) each show meaningful, statistically significant influence on operational and strategic outcomes. Technology adoption yields the largest single explanatory power for operational efficiency, while regulatory compliance has substantial commercial implications. Stakeholder engagement plays a key social role that supports stable operations and can complement compliance and technology investments.

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## 5. Conclusions

The questionnaire instrument is reliable for measuring regulatory compliance, market competitiveness, technology adoption, production efficiency, stakeholder engagement, and stakeholder commitment in the quarry industry context ( $n = 365$ ).

- Regulatory compliance is strongly and positively associated with market competitiveness; firms that comply more fully tend to achieve better market positions.
- Technology adoption is a primary driver of production efficiency; investments in modern machinery, automation, and digital monitoring significantly improve operational outcomes.
- Stakeholder engagement significantly fosters stakeholder commitment; sustained, participatory engagement reduces social friction and supports continuity of operations.

While each independent variable accounts for a meaningful share of variance in its outcome, substantial unexplained variance remains, indicating the need to consider complementary factors (finance, workforce skills, supply-chain logistics, macroeconomic conditions).

### 5.1. Recommendations

For Quarry Firms

- Prioritize compliance integration into business strategy: maintain permits, conduct periodic compliance audits, document environmental performance, and publicize compliance achievements to strengthen market reputation and access to contracts.
- Invest strategically in technology: target high-impact upgrades (energy-efficient crushers, automation for repetitive tasks, IoT/digital monitoring for predictive maintenance) that yield rapid gains in material recovery and reduced downtime.
- Strengthen stakeholder engagement programs: institutionalize community consultation protocols, establish grievance mechanisms, fund visible community development projects, and involve stakeholders in monitoring to build commitment and reduce project disruption.

For Researchers and Practitioners

- Investigate complementary predictors: future studies should include firm size, capital availability, workforce skill levels, and supply-chain variables to explain remaining variance in competitiveness and efficiency.

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### Compliance with ethical standards

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#### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

#### *Statement of ethical approval*

This study received ethical approval from Tertiary Education Trust Fund (TETFund) through the Directorate of Research and Development of the Federal Polytechnic, Idah. (TETF/ES/DR&D/CE/POLY/IDAH/IBR/2023/VOL.1).

#### *Statement of informed consent*

Informed consent was obtained from all participants

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## Appendix

### *Questionnaire — Sustainable Practices and Operational Efficiency of the Quarry Industry in North-Central Nigeria*

Instructions: Please respond to each statement using the 5-point Likert scale where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree. Tick or write your answer where appropriate. This questionnaire is for research purposes and your responses will be treated confidentially.

#### Section A: Respondent Information

- RESP\_ID: \_\_\_\_\_

- AGE: 18–29 [ ] 30–39 [ ] 40–49 [ ] 50+ [ ]
- GENDER: Male [ ] Female [ ] Other [ ]
- ROLE IN FIRM: Manager [ ] Supervisor [ ] Worker [ ] Community rep [ ] Regulator [ ] Other \_\_\_\_\_
- YEARS OF EXPERIENCE IN QUARRY INDUSTRY: \_\_\_\_\_ years
- LOCATION (State / Local Government Area): \_\_\_\_\_

Section B:

Regulatory Compliance (RC)

- RC1. The firm consistently adheres to national environmental regulations.
- RC2. The firm obtains and maintains necessary permits and licenses.
- RC3. The firm regularly reports environmental performance to authorities.
- RC4. The firm implements measures to control dust, noise, and vibration.
- RC5. The firm complies with occupational health and safety regulations.
- RC6. The firm conducts periodic compliance audits and corrective actions.

Section C: Market Competitiveness (MC)

- MC1. Our firm's product quality is competitive in the market.
- MC2. Our firm's pricing strategy improves market share.
- MC3. Compliance with regulations improves our firm's reputation.
- MC4. Clients prefer our products because of our compliance record.
- MC5. Regulatory compliance has improved access to contracts and markets.
- MC6. The firm's compliance reduces risk of legal actions and fines.

Section D: Technology Adoption (TA)

- TA1. The firm uses modern crushing and screening technologies.
- TA2. The firm applies automation or semi-automation in extraction/processing.
- TA3. The firm uses GPS/geomatics or remote sensing for planning.
- TA4. The firm employs digital monitoring (IoT/data analytics) for operations.
- TA5. The firm uses energy-efficient machinery and processes.
- TA6. The firm invests in regular technology upgrades.

Section E: Production Efficiency (PE)

- PE1. The firm achieves high material recovery rates.
- PE2. The firm minimizes downtime through maintenance practices.
- PE3. The firm meets production targets consistently.
- PE4. Technology has reduced production delays in our operations.
- PE5. Energy consumption per unit output has decreased over time.
- PE6. Waste generation per unit output is minimized.

Section F: Stakeholder Engagement (SE)

- SE1. The firm engages local communities before project actions.
- SE2. The firm provides regular information and feedback channels to stakeholders.
- SE3. The firm involves stakeholders in decision making where appropriate.
- SE4. The firm conducts community development projects.
- SE5. The firm addresses stakeholder concerns promptly.

Section G: Stakeholder Commitment (SC)

- SC1. Stakeholders consistently support the firm's projects.
- SC2. Stakeholders show trust in the firm's management and operations.
- SC3. Stakeholders collaborate with the firm on sustainability initiatives.

- SC4. Stakeholder support reduces community disruptions to operations.
- SC5. Stakeholders are willing to participate in monitoring and evaluation activities.

Section H: Open-ended

OE1. Please provide any additional comments or suggestions on sustainability practices and operational efficiency in quarry operations: