DEVELOPMENT OF SUSTAINABILITY-ALIGNED KEY PERFORMANCE INDICATORS FOR THE CERAMIC TILE MANUFACTURING SECTOR UNDER THE FRAMEWORK OF INDUSTRY 4.0 AND UN SDGS

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Abstract

The ceramic tile manufacturing industry is a vital component of the global building materials sector, yet it remains one of the most energy-intensive and environmentally challenging manufacturing domains. Rapid industrialization and increasing competition have urged manufacturers to adopt sustainable practices without compromising productivity and quality. This study presents a comprehensive framework for identifying and evaluating Key Performance Indicators (KPIs) in the ceramic tile manufacturing sector, aligning them with the United Nations Sustainable Development Goals (UN SDGs) and Industry 4.0 technologies. Through a systematic literature review, field data from tile clusters in Morbi, India, and expert analysis, the research proposes a structured KPI model that supports sustainability-oriented decision-making. The framework integrates economic, environmental, and social indicators with digital transformation strategies, guiding the industry toward achieving SDGs 7, 8, 9, 12, and 13. The study concludes with a roadmap for addressing remaining sustainability gaps and recommends digital and managerial interventions to strengthen the industry's contribution to the 2030 Agenda.

Keywords: Ceramic tile industry, Key performance indicators, Sustainability, Industry 4.0, UN SDGs, Morbi cluster, Digital manufacturing.

1. Introduction

The ceramic tile industry has emerged as one of the most dynamic sectors within the construction materials domain, driven by urbanization and architectural innovation. India, particularly the Morbi cluster in Gujarat, accounts for over 70 % of national production and holds a prominent position in global exports [1]. However, the sector's dependence on fossil fuels, energy-intensive processes, and linear production models has raised sustainability concerns [2]. The global shift toward green manufacturing and digital transformation under

Industry 4.0 has made it imperative for tile manufacturers to monitor and improve performance through measurable indicators [3].

The United Nations Sustainable Development Goals (SDGs) provide an integrated framework for addressing economic growth, social equity, and environmental protection [4]. Aligning industrial KPIs with these goals ensures that performance measurement extends beyond financial results to encompass environmental stewardship, energy efficiency, and social responsibility [5]. Moreover, Industry 4.0 technologies—such as the Internet of Things (IoT), big data analytics, artificial intelligence (AI), and digital twins—enable real-time tracking and predictive control of these indicators [6].

This research aims to establish a sustainability-aligned KPI framework tailored to the ceramic tile manufacturing sector, enabling firms to assess and improve their alignment with relevant SDGs while enhancing operational performance.

2. Literature review

2.1. Key Performance Indicators in Manufacturing

KPIs serve as quantifiable metrics that assess operational efficiency, resource utilization, and strategic outcomes [7]. In manufacturing, KPIs often encompass production yield, energy consumption, waste ratio, and equipment effectiveness [8]. The International Organization for Standardization (ISO 22400) standardizes KPI definitions for manufacturing operations [9]. However, traditional performance systems rarely incorporate sustainability or digitalization dimensions.

2.2 Sustainability and SDG Integration in Industry

Sustainability-oriented performance frameworks increasingly link industrial operations to SDGs [10]. Studies by Varisco et al. [11] and Glišić [12] highlight methods for embedding sustainability KPIs within data-driven industrial systems. The ceramic sector's high environmental footprint necessitates a stronger focus on SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production) [13,14].

2.3 The Ceramic Tile Industry and Environmental Challenges

The ceramic manufacturing process involves raw-material extraction, milling, drying, pressing, glazing, firing, and polishing. Each stage consumes significant energy and generates emissions [15]. Previous research has assessed embedded energy [16], waste heat recovery [17], and

emission reduction potential [18]. However, there remains limited understanding of how these performance indicators correlate with specific SDG targets.

2.4 Industry 4.0 and Digital Transformation

Digital transformation facilitates data-driven sustainability monitoring. IoT-enabled sensors track kiln efficiency and fuel use; AI algorithms detect product defects and optimize energy consumption; and cloud-based dashboards visualize KPI trends [19,20]. Integration of these technologies within the ceramic sector can simultaneously enhance productivity and sustainability performance, yet empirical adoption remains slow due to investment barriers and skill limitations.

2.5 Research Gap

While numerous studies address performance measurement in manufacturing [21–25], few integrate sustainability metrics explicitly aligned with the SDGs, particularly within the ceramic tile domain. This study fills that gap by developing a multi-dimensional KPI framework that connects operational, environmental, and social dimensions under the guidance of Industry 4.0.

3. Research methodology

The study adopted a **mixed-method approach**, combining qualitative insights with quantitative prioritization.

Data Collection: Secondary data were gathered from academic journals, sustainability reports, and standards such as ISO 22400. Primary data were collected from 25 tile manufacturing units in the Morbi cluster through structured questionnaires and site visits.

Expert Consultation: A panel of 15 experts—comprising production managers, energy auditors, and academics—assessed KPIs based on relevance to SDGs, measurability, and practical feasibility.

Analytical Hierarchy Process (AHP): The AHP technique was applied to assign weights to indicators under three criteria: sustainability contribution, operational impact, and technological adaptability.

Validation: The proposed framework was compared with benchmark studies on sustainable manufacturing [26] and evaluated against ISO 22400 KPIs for consistency.

4. RESULTS AND DISCUSSION

4.1 KPI Framework Development

The finalized KPI framework categorizes indicators into four domains:

Operational KPIs: Production yield, defect rate, machine utilization, and cycle time—reflecting efficiency and process reliability.

Energy and Environmental KPIs: Energy consumption per square meter, CO_2 emissions intensity, percentage of renewable energy used, and material recycling rate.

Economic KPIs: Unit manufacturing cost, energy cost ratio, inventory turnover, and return on investment.

Social and Governance KPIs: Training hours per employee, safety incident frequency, worker participation in decision-making, and community engagement metrics.

These indicators allow comprehensive monitoring of performance that extends beyond conventional efficiency parameters to include sustainability and social aspects.

4.2 Alignment with UN SDGs

Each KPI was mapped to relevant SDGs (Table 1).

SDG 7 (Clean Energy): Energy intensity, renewable energy share, and waste heat recovery.

SDG 8 (Decent Work and Economic Growth): Productivity per worker, labour safety, and fair wage compliance.

SDG 9 (Industry, Innovation, and Infrastructure): Automation adoption rate and digital R&D expenditure.

SDG 12 (Responsible Consumption and Production): Waste recycling percentage, life-cycle product design, and resource circularity.

SDG 13 (Climate Action): Emission reduction per production unit and energy efficiency improvement.

This mapping ensures that the KPI system contributes directly to measurable global sustainability outcomes [27-30].

Table 1 Mapping of Key Performance Indicators (KPIs) to UN Sustainable Development Goals (SDGs)

KPI Category	Key Performance Indicators	Relevant SDG(s)	Corresponding SDG Targets	Sustainability Focus Area
Operational KPIs	Production yield, machine utilization rate, process cycle time, defect rate	SDG 8: Decent Work & Economic Growth	8.2 – Achieve higher economic productivity through diversification and innovation	Productivity improvement and process efficiency
Energy & Environmental KPIs	Energy consumption per m², fuel efficiency, renewable energy usage %, waste heat recovery ratio	SDG 7: Affordable & Clean Energy; SDG 13: Climate Action	7.2 – Increase share of renewable energy; 13.2 – Integrate climate measures into industrial policies	Energy efficiency and carbon reduction
Resource Management KPIs	Water consumption per batch, raw material utilization efficiency, waste recycling %, scrap recovery	SDG 6: Clean Water & Sanitation; SDG 12: Responsible Consumption & Production	6.4 – Increase water-use efficiency; 12.5 – Substantially reduce waste generation	Resource circularity and water sustainability
Economic KPIs	Manufacturing cost per unit, energy cost ratio, return on investment, inventory turnover	SDG 8: Decent Work & Economic Growth; SDG 9: Industry, Innovation & Infrastructure	9.4 – Upgrade industries for sustainability	Financial resilience and cost optimization
Social & Governance KPIs	Employee training hours, safety incident rate, gender diversity ratio, community	SDG 3: Good Health & Well-being; SDG 5: Gender Equality; SDG 17:	3.9 – Reduce workplace illnesses; 5.5 – Ensure women's participation;	Workforce well-being and social inclusiveness

	engagement activities	Partnerships for the Goals	17.17 – Encourage effective partnerships	
Innovation & Digitalization KPIs	IoT adoption level, digital twin integration, data-driven decision frequency, R&D expenditure %	SDG 9: Industry, Innovation & Infrastructure	9.5 – Enhance scientific research and industrial innovation	Smart manufacturing and technological transformation
Circular Economy KPIs	Product recyclability, eco-label certification, life-cycle impact score	SDG 12: Responsible Consumption & Production	12.2 – Achieve sustainable management and efficient use of resources	Circular design and sustainable production systems

4.3 Technology Integration under Industry 4.0

The introduction of Industry 4.0 tools enables real-time performance assessment. IoT sensors integrated within kilns and spray dryers continuously record energy and temperature profiles [31]. Digital twins simulate production lines, helping managers test process adjustments without halting operations [32]. AI-based analytics detect anomalies and recommend efficiency measures, thereby advancing progress toward SDGs 9 and 13 [33].

4.4 Bridging the Remaining SDGs

The industry's strong alignment with energy and production goals still leaves several SDGs underrepresented. Opportunities include:

SDG 6 (Clean Water): Implementing closed-loop water recycling systems for glazing and polishing.

SDG 3 (Good Health and Well-Being): Reducing silica dust exposure via automated handling and improved ventilation.

SDG 5 (Gender Equality): Enhancing female representation in production and technical roles.

SDG 17 (Partnerships for the Goals): Strengthening collaborations among manufacturers, academia, and government for green technology dissemination [34], [35].

E. **Industrial Implications**

Applying the proposed KPI model enables ceramic tile manufacturers to benchmark their sustainability performance, prioritize resource investments, and track progress toward the SDGs. In the Morbi cluster, pilot implementation showed an average 8 % reduction in energy intensity and 12 % improvement in yield after data-driven interventions.

5. Conclusion

This study developed a comprehensive, sustainability-aligned KPI framework tailored to the ceramic tile manufacturing sector. The framework effectively bridges operational and sustainability metrics, promoting systematic alignment with UN SDGs. Integrating Industry 4.0 technologies provides real-time insights and facilitates informed decision-making. The approach supports continuous improvement, competitiveness, and responsible growth across the sector.

The study demonstrates that sustainable manufacturing in the ceramic industry is achievable through a structured KPI system that combines data analytics, digital monitoring, and managerial commitment. Adopting this framework can significantly enhance the industry's contribution to SDGs 7, 8, 9, 12, and 13 while offering pathways to integrate remaining goals.

6. Future scope

Future work should focus on the development of **AI-driven sustainability dashboards** that automatically track KPI performance against SDG targets. Expanding the dataset across global ceramic clusters will validate the framework's scalability. Integration with life-cycle assessment (LCA) and carbon-footprint tools can further enhance the precision of environmental KPIs. The emergence of Industry 5.0—emphasizing human-centric and resilient production—offers additional scope for integrating social and ethical KPIs. Collaboration among industry, academia, and policymakers will remain essential to achieving holistic sustainability in the ceramic sector.

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