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THE ROLE OF INDUSTRIAL ENGINEERING IN ADVANCING SUSTAINABLE MANUFACTURING AND QUALITY COMPLIANCE IN GLOBAL ENGINEERING SYSTEMS

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Abstract

This study addresses the persistent gap in empirical evidence on how industrial engineering practices jointly drive sustainable manufacturing performance and quality compliance in global engineering systems. The purpose is to quantify these relationships using a quantitative cross sectional, case-based design grounded in enterprise cases from globally integrated manufacturing organizations. Primary data were collected through a structured Likert five-point questionnaire, yielding 248 usable responses from professionals in industrial engineering, production, quality and sustainability functions. Key variables include industrial engineering practices, sustainable manufacturing performance and quality compliance, measured as reliable multi-item indices. The analysis plan combined descriptive statistics, reliability and correlation analysis, multiple regression with mediation testing, and a Random Forest regression model for enhanced prediction. Industrial engineering practices showed a high mean of 3.92, while sustainability and quality compliance scored 3.68 and 3.87 respectively, with strong internal consistency (Cronbach's alpha ranging from 0.89 to 0.91). Industrial engineering practices were strongly correlated with sustainability ($r = 0.64$, $p < .001$) and compliance ($r = 0.58$, $p < .001$), and significantly predicted sustainable performance ($\beta = 0.61$, adjusted $R^2 = 0.43$) and quality compliance ($\beta = 0.57$, adjusted $R^2 = 0.33$). When sustainability was included, the model for compliance improved (adjusted $R^2 = 0.49$) and its mediating role was confirmed, while a Random Forest model further increased predictive power ($R^2 = 0.62$). Overall, the findings show that mature industrial engineering capabilities are a critical pathway to both higher sustainable manufacturing performance and stronger quality compliance in global enterprise manufacturing systems.

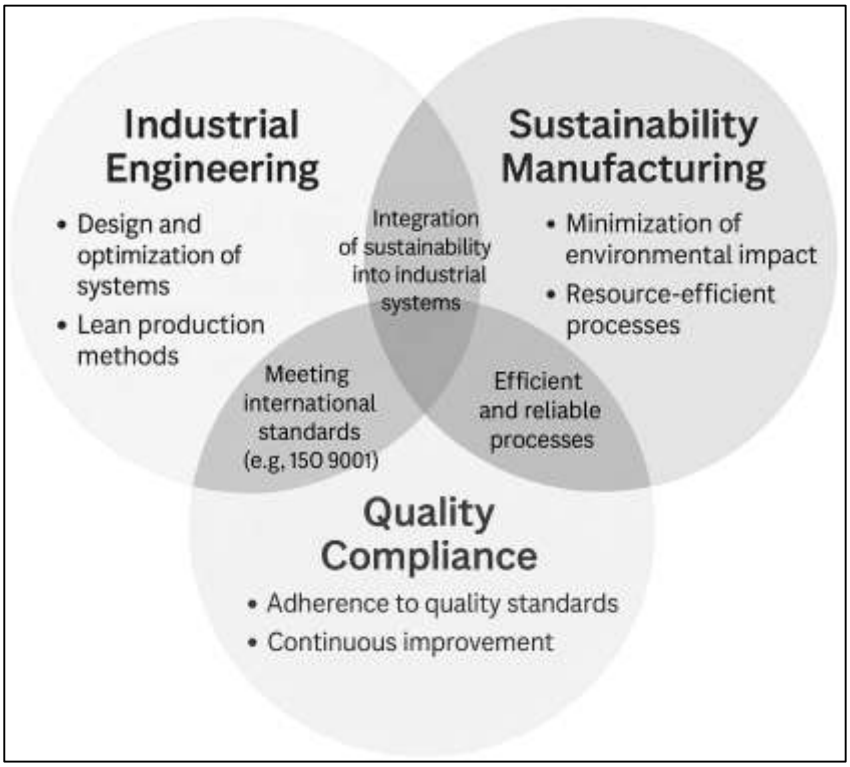
Keywords

Industrial Engineering Practices; Sustainable Manufacturing Performance; Quality Compliance; Global Engineering Systems; Random Forest Regression;

INTRODUCTION

Industrial engineering is broadly concerned with the design, improvement, and integration of people, materials, information, equipment, and energy to produce goods and services efficiently and reliably across complex socio-technical systems. In contemporary manufacturing, this discipline sits at the intersection of operations research, systems engineering, and management science, providing methods for optimizing workflows, reducing waste, and enhancing quality in globally distributed production networks. Sustainable manufacturing extends this remit by emphasizing production processes that conserve resources, minimize environmental burdens, and maintain economic viability while protecting worker safety and community well-being (Feng et al., 2008). Life cycle–oriented conceptions of sustainability position manufacturing as part of a global engineering system where material and energy flows, regulatory pressures, and stakeholder expectations interact across borders (Finkbeiner et al., 2010). Within this context, quality compliance particularly alignment with international standards such as ISO 9001 becomes both a technical and organizational requirement, linking process control with customer satisfaction, regulatory conformity, and reputational legitimacy (Ghadimi et al., 2017). The convergence of industrial engineering, sustainable manufacturing, and quality compliance therefore represents a strategic domain for organizations operating in global engineering systems, where performance is judged not only on cost and delivery, but also on resource stewardship and conformity to international quality norms.

Figure 1: Venn Diagram Illustrating the Overlap between Industrial Engineering



Sustainable manufacturing research has progressively moved from high-level principles to more formalized frameworks in which industrial engineering plays a central coordinating role. Early contributions emphasized the need to embed environmental and social concerns into product, process, and system design decisions, calling for integrated optimization models that span multiple decision levels (Jayal et al., 2010). Subsequent work framed sustainable manufacturing as an evolution of conventional manufacturing, in which process planning, facility layout, and production control are re-designed around energy efficiency, material productivity, and worker well-being, often using tools that originate in industrial engineering such as value stream mapping, line balancing, and simulation (Rosen & Kishawy, 2012). Reviews of the field highlight how industrial engineering methods provide the analytical backbone for modeling trade-offs between cost, throughput, and environmental performance, particularly when integrating lean production with sustainability initiatives (Abdulla & Ibne, 2021; Weinert et al., 2017). These studies show that industrial engineers increasingly act as system integrators who translate sustainability goals into operational targets, process redesigns, and performance indicators within manufacturing environments (Habibullah & Foysal, 2021; Sarwar, 2021). A major strand of this literature emphasizes life cycle–based approaches as the methodological foundation for assessing sustainability in manufacturing. Life Cycle Sustainability Assessment (LCSA) extends traditional life cycle assessment by combining environmental, economic, and social indicators into a single analytical framework for decision-making (Musfiqur & Saba, 2021; Redwanul et al., 2021; Sampaio et al., 2009). Industrial engineering contributes by developing models, data collection protocols, and optimization procedures that allow LCSA results to inform process design, capacity planning, and technology selection in factories and networks (Tarek & Praveen, 2021; Muhammad & Shahrin, 2021). Recent reviews synthesize diverse sustainability assessment methods based on life cycles, observing that multi-criteria decision-making and multi-objective optimization techniques are increasingly employed to compare process alternatives, technology options, and configuration scenarios in manufacturing systems (Saikat, 2021; Sala et al., 2019; Shaikh & Aditya, 2021). This body of work underlines the need for industrial engineering models that can translate complex sustainability indicators into actionable process changes, linking life cycle metrics with shop-floor performance measures such as throughput, scrap rate, and energy use (Amin, 2022; Ariful, 2022).

The sustainability challenges of global engineering systems extend beyond individual factories to multinational supply networks. Strategic models of sustainable supply chains show how decisions on plant location, sourcing, transportation, and end-of-life management affect cumulative emissions, resource consumption, and social impacts at an industry scale (Nahid, 2022; Hossain & Milon, 2022; Sampaio et al., 2012). Industrial engineering methods, particularly network design, simulation, and optimization, are used to evaluate scenarios where environmental indicators such as CO_2 emissions are minimized alongside total cost and service level objectives. In the automotive sector, for example, sustainable supply chain management frameworks capture how design, production, logistics, and recycling decisions interact under stringent environmental and safety regulations (Izogo & Ogba, 2015; Mominul et al., 2022; Rabiul & Praveen, 2022). Social sustainability perspectives add further complexity by examining working conditions, community impacts, and stakeholder relationships in emerging-economy manufacturing hubs, requiring additional constructs and metrics beyond traditional production indicators (Rakibul & Samia, 2022; Saikat, 2022). Within this environment, quality compliance must be maintained across multiple tiers, suppliers, and regulatory regimes, positioning industrial engineering as a key discipline for coordinating design standards, process capabilities, and audit requirements across global engineering systems (Maniruzzaman et al., 2023; Kanti & Shaikat, 2022).

Quality management and quality compliance form a second foundational pillar in this domain, grounded in standardized management systems and continuous improvement philosophies. ISO 9001–based quality management systems provide a structured framework for documenting processes, controlling variation, and demonstrating conformity, and they have been widely adopted across manufacturing industries as a prerequisite for participation in international supply chains (Gunasekaran & Spalanzani, 2012; Arif Uz & Elmoon, 2023; Tarek, 2023). Empirical studies indicate that ISO 9001 certification is frequently associated with improvements in operational performance, financial results, and process discipline, although the magnitude and consistency of these benefits vary by context (Gbededo et al., 2018; Mushfequr & Ashraful, 2023; Shahrin & Samia, 2023). Complementary work conceptualizes ISO 9001 research itself, mapping recurring questions and methodological approaches and identifying a need for more rigorous analytical and longitudinal designs (Amindoust & Saghafinia, 2019; Muhammad & Redwanul, 2023; Muhammad & Redwanul, 2023). From a sustainability perspective, total quality management (TQM) principles customer focus, continuous improvement, and employee involvement have been linked to sustained organizational development and long-term performance, with TQM framed as a pathway for embedding sustainability into management systems (Razia, 2023; Todorut, 2012; Zayadul, 2023). These insights are highly relevant for industrial engineers who design and improve processes under both sustainability and compliance constraints.

The interface between total quality management and sustainable development has attracted growing research attention, yielding conceptual and empirical models that treat quality and sustainability as mutually reinforcing. Literature reviews on the support of quality management for sustainable development identify multiple themes, including the use of quality tools to integrate environmental and social requirements into product development and process management (Siva et al., 2016). Case-based and survey-based studies show that organizations leveraging TQM practices such as systematic problem solving, process standardization, and employee training often report enhanced stakeholder satisfaction and more resilient performance profiles (Traverso et al., 2012). In the context of services and customer-facing operations, work on service quality and loyalty underscores how structured quality practices translate into reliable service delivery and relational outcomes, strengthening the business case for robust quality systems (Sampaio et al., 2011). Excellence models such as the European Foundation for Quality Management (EFQM) framework provide an additional theoretical foundation by explicitly linking leadership, process management, and key results with broader notions of organizational excellence and sustainability (Seliger et al., 2008). These frameworks provide conceptual guidance for industrial engineers seeking to integrate process optimization, behavioral factors, and governance mechanisms into the design of sustainable, quality-compliant manufacturing systems.

At the same time, quality and sustainability considerations are increasingly examined in complex, safety-critical, or disruption-prone sectors where continuity of operations is a major concern. Studies in healthcare, for example, illustrate how matrices of functions and organizations can be developed to ensure continuous service provision under disruptive conditions, integrating quality management principles with risk-informed planning (Seliger et al., 2008). Social sustainability research in supply chains complements this perspective by articulating constructs and measurement instruments for issues such as labor conditions, equity, and community impact, providing guidance on how to incorporate these dimensions into performance management systems (Mani et al., 2016). In manufacturing environments, such insights can be translated into design criteria for work systems, supplier selection practices, and audit schemes that extend beyond purely technical quality metrics. Industrial engineering, with its focus on work systems, process flows, and resource allocation, is well placed to operationalize these multidimensional requirements through layout design, standard work, scheduling policies, and control charts that jointly reflect sustainability and quality compliance objectives (Kajihara et al., 2016).

Overall, the existing literature demonstrates that industrial engineering techniques are deeply embedded in both sustainable manufacturing and quality management domains, yet much of the evidence remains fragmented across methodological traditions, sectors, and geographic contexts. Life cycle–oriented studies offer detailed assessments of environmental and social impacts but often treat process design and industrial engineering interventions only at an aggregate level (Joiner, 2007). Research on ISO 9001, TQM, and excellence models provides rich insights into organizational performance and stakeholder satisfaction, although the specific mechanisms linking industrial engineering decisions such as line configuration, automation choices, or digital quality tools to sustainability and compliance outcomes are less frequently quantified (Kannegiesser et al., 2014). Similarly, global supply chain models evaluate carbon emissions and cost at network scale, yet often treat quality compliance and industrial engineering practice as background assumptions rather than focal explanatory variables (Kannegiesser & Günther, 2013). This convergence of partially connected strands highlights the need for empirical, quantitative research that explicitly examines the role of industrial engineering practices in advancing sustainable manufacturing and quality compliance within global engineering systems, thereby motivating the present study's focus on cross-sectional, case-based analysis using descriptive statistics, correlation, and regression modeling (Kim et al., 2010).

The overarching objective of this study is to examine how industrial engineering practices contribute to advancing sustainable manufacturing and strengthening quality compliance within global engineering systems, using a rigorous quantitative and case-study–based approach. More specifically, the research is designed to achieve several interrelated objectives that translate the broad aim into measurable analytical tasks. First, the study seeks to assess the current level and pattern of adoption of core industrial engineering practices in the selected manufacturing organizations, including their use in process design, work measurement, line balancing, lean implementation, and data-driven decision-making. Second, it aims to evaluate the extent to which these practices are associated with improvements in sustainable manufacturing performance, as reflected in indicators such as resource efficiency, waste reduction, energy management, and environmentally conscious process design. Third, the study investigates the influence of both industrial engineering practices and sustainable manufacturing performance on quality compliance, focusing on dimensions such as adherence to documented procedures, audit readiness, reduction of non-conformances, and consistency of product or service quality. Fourth, the research examines the potential mediating role of sustainable manufacturing performance in the relationship between industrial engineering practices and quality compliance, thereby clarifying whether sustainability-oriented outcomes act as a pathway through which industrial engineering exerts its influence on compliance. Finally, the study develops and evaluates a predictive Random Forest regression model for quality compliance based on industrial engineering and sustainability variables, and compares its predictive performance with that of traditional linear regression models. Through these objectives, the study aligns its research questions and hypotheses with a coherent empirical strategy, grounded in Likert-scale survey data, descriptive statistics, correlation analysis, regression modeling, and machine learning–based prediction, thereby providing a clear logical bridge between the conceptual framing of the topic and the analytical procedures employed in the subsequent sections of the paper.

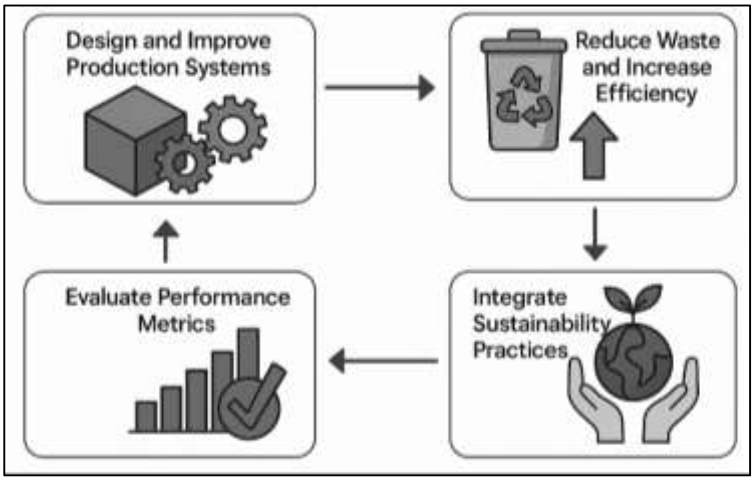
LITERATURE REVIEW

The literature review for this study positions industrial engineering, sustainable manufacturing, and quality compliance within a shared analytical space, in order to understand how these domains intersect in the context of global engineering systems. Over the past two decades, industrial engineering has evolved from a focus on efficiency and cost minimization to a broader concern with the design of socio-technical systems that can deliver robust performance under demanding environmental, regulatory, and market conditions. Sustainable manufacturing emerged in parallel as a response to growing awareness of environmental degradation, resource constraints, and social responsibility, and it reframed traditional production objectives by placing resource efficiency, emission reduction, and worker well-being alongside throughput, cost, and quality. Quality compliance developed along its own trajectory, driven by the diffusion of management system standards, sector-specific regulations, and customer requirements, and it provided organizations with structured frameworks for documenting processes, controlling variation, and demonstrating conformity. The literature review therefore begins by tracing how industrial engineering tools and methods have been applied to support sustainability goals at the product, process, and system levels, emphasizing their role in modeling, optimizing, and monitoring complex manufacturing operations. It then examines research on quality management and quality compliance, with particular attention to ISO-based systems, total quality management, and excellence models that connect process discipline with performance outcomes. A further strand of literature situates these discussions within globalized production and supply networks, where sustainability and compliance are no longer confined to individual plants but extend across multiple tiers and regions. Within this broader landscape, conceptual and theoretical contributions propose frameworks that integrate industrial engineering, sustainability, and quality, often drawing on systems thinking and socio-technical perspectives to explain how interventions in work design, process flow, and information systems propagate through an organization. However, these streams of work vary in their methodological focus, with some emphasizing qualitative insights and conceptual models, while others rely on case studies, surveys, or optimization models that address only one or two of the key constructs at a time. The literature review thus serves to synthesize these strands, identify the constructs and relationships most relevant to the present study, and highlight the specific empirical and conceptual gaps that justify a quantitative, case-based investigation of the role of industrial engineering in advancing sustainable manufacturing and quality compliance in global engineering systems.

Industrial Engineering for Sustainable Manufacturing

Industrial engineering has provided the methodological backbone for transforming traditional factories into sustainable, high-performing production systems by systematically designing, improving, and integrating people, materials, information, and technology flows. Early empirical work showed that classical industrial engineering tools such as value stream mapping, line balancing, and work study can dramatically reduce lead time, inventory, and non-value-added activities, which indirectly lowers energy use and material waste (Abdulmalek & Rajgopal, 2007). As sustainability pressures have intensified, these tools have been reframed from a narrow cost-efficiency lens toward the broader triple bottom line of economic, environmental, and social performance. Lean manufacturing, as a core industrial engineering philosophy, emphasizes the elimination of muda (waste) in all its forms; when mapped against environmental waste streams such as scrap, emissions, and unnecessary transport, the same techniques that increase throughput can also mitigate environmental impacts. Within global engineering systems, this dual emphasis on productivity and eco-efficiency has made industrial engineering a critical enabler of cleaner production strategies in energy-intensive sectors like metals, automotive, and electronics, where marginal improvements in process efficiency translate into substantial carbon and resource savings.

Figure 2: Industrial Engineering Foundations for Sustainable Manufacturing



Building on these foundations, researchers have articulated how lean and related industrial engineering approaches can be integrated with supply chain management to support sustainability at the network level, not just within single plants. A comprehensive review of lean management and supply chain management literature, for instance, shows that standardized work, pull systems, and continuous improvement routines can be aligned with environmental objectives when extended upstream to suppliers and downstream to customers (Martínez-Jurado & Moyano-Fuentes, 2014). This alignment requires industrial engineers to redesign material and information flows across organizational boundaries, reducing overproduction, unnecessary transport, and redundant packaging while stabilizing process variability. In parallel, empirical evidence from European manufacturing firms demonstrates that specific lean tools such as 5S, value stream mapping, cellular manufacturing, single-minute exchange of dies (SMED), and total productive maintenance (TPM) can be deliberately deployed to cut energy consumption, reduce scrap, and improve environmental indicators, rather than treating "green gains" as incidental side effects of cost reduction (Chiarini, 2014). These studies collectively position industrial engineering not only as a discipline for operational optimization, but as an orchestrator of sustainability-oriented process innovation.

At the same time, the literature cautions that the relationship between industrial engineering–driven lean programs and sustainability outcomes is complex and context dependent, calling for more nuanced integration frameworks. A systematic review of lean–green research highlights that while many case studies report concurrent improvements in efficiency and environmental performance, others point to trade-offs when lean initiatives neglect environmental metrics or shift burdens elsewhere in the value chain (Garza-Reyes, 2015). More recent quantitative work using structural equation modeling explores how lean manufacturing and Industry 4.0 technologies jointly influence the economic, environmental, and social pillars of sustainability, finding that digitalization can amplify or mediate the sustainability effects of lean and related industrial engineering interventions (Varela et al., 2019). Together, these contributions suggest that industrial engineering foundations for sustainable manufacturing must be embedded in a systems perspective that explicitly models feedback loops, cross-functional coordination, and life-cycle impacts.

Quality Compliance in Global Engineering Systems

Quality compliance in global engineering systems refers to the systematic adherence to internal quality standards, external regulations, and customer-specific requirements across geographically dispersed facilities and supply networks. In highly regulated and competitive industries, compliance has evolved from a narrow focus on documentation and inspection to a broader, system-level concept embedded within quality management systems and supply chain structures. Empirical studies of supply chain quality management show that quality practices must extend beyond the focal plant to upstream suppliers and downstream customers, and that these practices significantly affect conformance quality and customer satisfaction (Zeng et al., 2013). In this view, compliance is not simply "passing audits" but ensuring that processes, interfaces, and information flows are designed to maintain consistent quality levels across multiple tiers. Structural equation modeling of supply chain quality management further indicates that internal quality management is a dominant driver that shapes how firms interact with suppliers and customers, and thus underpins overall quality performance (Lin et al., 2005). For global engineering systems, these findings imply that quality compliance must be rooted in robust internal systems such as documented procedures, statistical process control, and management review while being extended through coordinated practices that govern supplier participation, joint problem-solving, and shared performance indicators.

Figure 3: Key Components of Quality Compliance Across Global Engineering Networks

Within this systems perspective, quality compliance is closely tied to the maturity and effectiveness of the quality management system (QMS) implemented across the organization. Research on supply chain quality management in manufacturing firms demonstrates that firms with higher levels of QMS sophistication exhibit stronger knowledge of their supply chain partners, clearer quality specifications, and more collaborative customer–supplier relationships, which in turn improve product quality outcomes (Sila et al., 2006). In addition, multi-country empirical work reveals that quality management practices such as top management leadership, quality information systems, and process control cohere into an integrated infrastructure that supports quality results, including defect reduction and improved reliability (Arauz et al., 2009). From a compliance standpoint, these infrastructures provide the mechanisms for ensuring that standards, procedures, and corrective actions are consistently deployed and monitored across plants and regions. Supply chain quality management models suggest that internal quality practices influence supplier and customer-facing quality interactions, and that downstream quality collaboration often mediates the impact of internal quality on customer satisfaction (Ilkay & Aslan, 2012). As global engineering systems rely increasingly on multi-tier sourcing and contract manufacturing, the ability to diffuse QMS practices across organizational boundaries becomes critical for maintaining uniform compliance with international standards, sectoral regulations, and customer-specific quality requirements.

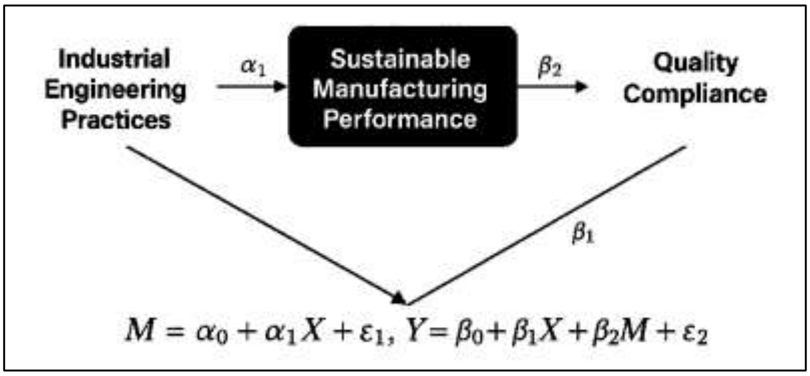
Quality compliance also plays a strategic role when organizations adopt formal quality management standards such as ISO 9001 across distributed operations. Empirical evidence from small and medium-sized enterprises shows that ISO 9001 certification is associated with better performance outcomes, but that the magnitude of the effect depends on whether the motivations for certification are internal (improvement-oriented) or external (market- or customer-driven) (Lin et al., 2005). In global engineering systems, this distinction is particularly relevant, because certification may be pursued to satisfy international customers or regulatory bodies, yet its compliance benefits materialize only when the standard is genuinely integrated into everyday processes and decision structures. Studies of quality management change in Japanese manufacturing firms highlight that QMS implementation is not static; managerial emphasis on different quality practices shifts over time, shaping how organizations sustain improvements and adapt to evolving requirements (Arauz et al., 2009). At the interface of quality compliance and global supply chains, supply chain quality management frameworks indicate that integrated quality practices combining internal quality management, supplier participation, and customer-focused quality activities are positively linked to both conformance quality and customer satisfaction, reinforcing the business case for compliance investments (Lin et al., 2005). Together, these studies suggest that quality compliance in global engineering systems is best understood as an emergent property of aligned QMS infrastructures, supply chain quality practices, and strategic use of international standards, rather than as a narrow, audit-oriented function.

Theoretical Framework

Industrial engineering, sustainable manufacturing, and quality compliance in global engineering systems can be anchored in systems thinking and socio-technical systems theory, both of which view organizations as complex, open systems composed of interdependent social and technical subsystems. Systems thinking emphasises feedback loops, non-linearity, and emergent behaviour, arguing that interventions at one point in a production system can have delayed and diffuse consequences elsewhere in the network (White & Mingers, 2010). From this perspective, production plants, engineering centres, and supply chain nodes are not isolated units but components of a wider system in which materials, information, people, and technologies interact continuously. Socio-technical systems theory extends this logic by proposing that organizational performance depends on the joint optimization of technical structures (equipment, workflows, information systems, standards) and social structures (skills, roles, culture, power relations), rather than privileging one over the other (Jackson, 2009). Industrial engineering practices such as work study, line balancing, standardized work, and statistical process control can therefore be conceptualised as technical design levers that must be aligned with human factors, organizational routines, and learning processes if they are to support sustainable manufacturing and robust quality compliance. Within this framework, sustainable manufacturing performance and quality compliance are emergent properties of socio-technical alignment, arising when process designs, technologies, worker competences, and governance mechanisms are coherently configured across global plants and supply chain partners (White & Mingers, 2010).

A complementary theoretical pillar for this research is the resource-based view (RBV), which explains performance differences in terms of valuable, rare, inimitable, and non-substitutable resources and capabilities that firms configure and deploy over time (Kraaijenbrink et al., 2010). Industrial engineering can be interpreted as a bundle of organizational capabilities – including process design expertise, analytical skills, continuous improvement routines, and data-driven decision-making – that enable firms to configure production systems in ways that support both sustainable manufacturing and high levels of quality compliance. Under an RBV logic, organizations that have developed stronger industrial engineering capabilities can be expected to achieve superior environmental and quality performance because they are better able to identify inefficiencies, re-engineer processes, and institutionalise best practices across geographically dispersed facilities (Yeung et al., 2011). However, these capabilities operate within institutional environments shaped by regulations, industry standards, and stakeholder expectations. Institutional theory highlights how organizations adopt formal structures such as ISO-based quality management systems in response to coercive, normative, and mimetic pressures, gaining legitimacy and access to markets, but also facing risks of symbolic adoption or decoupling if internal practices do not genuinely change (Imran & Kantola, 2019). In global engineering systems, the interaction between internally developed industrial engineering capabilities (RBV) and externally imposed quality and sustainability norms (institutional theory) helps explain why some firms convert industrial engineering practices into real sustainability and compliance improvements, while others focus mainly on certification and signalling (Jackson, 2009).

Figure 4: Mediation Model of Industrial Engineering

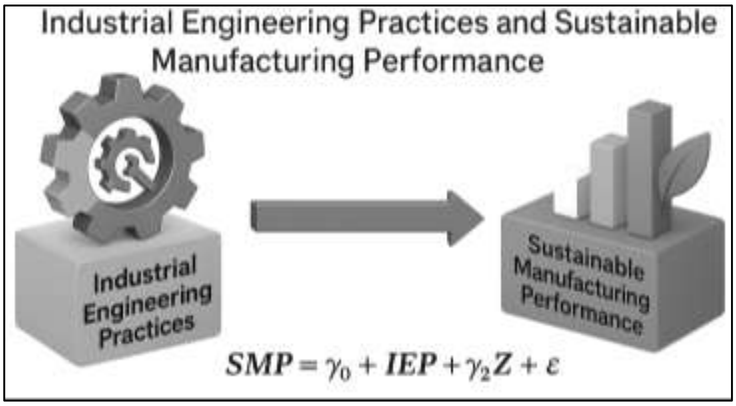


Bringing these perspectives together, the theoretical framework for this study specifies industrial engineering practices as the primary explanatory construct, sustainable manufacturing performance as an intermediate outcome, and quality compliance as the final outcome within an integrated socio-technical, resource-based, and institutional context. Conceptually, industrial engineering practices (X) are expected to influence sustainable manufacturing performance (M) and quality compliance (Y) through both direct and indirect pathways. In a linear mediation structure, this can be expressed as $M = \alpha_0 + \alpha_1 X + \varepsilon_1, Y = \beta_0 + \beta_1 X + \beta_2 M + \varepsilon_2,$
where $\alpha_1$captures the effect of industrial engineering practices on sustainable manufacturing performance, $\beta_1$represents the direct effect of industrial engineering on quality compliance, and $\beta_2$represents the additional contribution of sustainability performance to compliance outcomes. The indirect effect of industrial engineering practices on quality compliance is given by $\alpha_1 \times \beta_2$, and the total effect is $\beta_1 + (\alpha_1 \times \beta_2)$. Within an RBV interpretation, X is an observable manifestation of underlying industrial engineering capabilities, while M and Y reflect performance consequences that emerge from socio-technical alignment and institutionalised quality requirements (Kraaijenbrink et al., 2010). Recent work on Industry 4.0 integration has further argued that socio-technical perspectives are essential for combining advanced digital technologies with human competences and organizational processes, reinforcing the view that sustainable, quality-compliant performance arises from the co-evolution of technical architectures and social systems in manufacturing (Imran & Kantola, 2019). In this study, the theoretical framework thus justifies the specification of hypotheses linking industrial engineering practices, sustainable manufacturing, and quality compliance, and supports the use of mediation-type regression models to test those relationships empirically within global engineering systems.

Conceptual Framework

The first conceptual framework in this study specifies how industrial engineering practices are expected to influence sustainable manufacturing performance at the plant and system levels. Industrial engineering practices are conceptualized as a composite capability that includes structured process analysis (e.g., value stream mapping), standardized work design, pull and flow principles, setup time reduction, and systematic waste elimination. Within this framework, these practices are not treated as purely cost-reduction tools but as levers that shape material, energy, and information flows in ways that directly affect environmental and resource-related outcomes. Empirical and conceptual work on environmentally lean production, for example, has shown that integrating environmental indicators into lean tools such as value stream mapping makes it possible to visualize how process changes simultaneously influence time, cost, and environmental waste streams (Roosen & Pons, 2013). Simulation-based studies further demonstrate that alternative combinations of lean and "green" strategies can be tested virtually, revealing how different industrial engineering interventions alter throughput, inventory, and environmental impact at the same time (Diaz-Elsayed et al., 2013). In this conceptualization, industrial engineering practices are viewed as structured interventions in the socio-technical design of manufacturing systems, and their intensity of implementation is captured through multi-item Likert-scale constructs that reflect the degree to which lean, standardized work, continuous improvement, and energy-aware planning have been embedded in daily operations.

Figure 5: Framework Linking Industrial Engineering Practices



Sustainable manufacturing performance is conceptualized as a multi-dimensional outcome construct that reflects how effectively a production system uses resources while maintaining required output levels and product quality. From an energy and resource perspective, sustainable performance involves reducing total energy consumption, shifting to lower-impact energy sources, minimizing material scrap and rework, optimizing auxiliary systems, and designing processes that support future circularity. Reviews of energy consumption reduction technologies in manufacturing highlight the need to consider entire manufacturing systems, rather than individual machines, because many savings opportunities emerge from coordinated scheduling, process chain optimization, and layout redesign classic industrial engineering domains (Park et al., 2009). More recent work on "green value stream mapping" proposes new indicators for evaluating both productivity and environmental performance along a process chain, reinforcing the idea that sustainable outcomes can be directly traced back to process design decisions such as batch size, transport distances, and buffer locations (Muñoz-Villamizar et al., 2019). Complementary research on integrated lean–green practices introduces the concept of "carbon–value efficiency," which measures the economic value created per unit of carbon emitted and provides a quantitative link between industrial engineering decisions, process efficiency, and greenhouse gas emissions (Ng et al., 2015). In this framework, sustainable manufacturing performance is operationalized as an index derived from survey items capturing perceived improvements in energy intensity, material efficiency, waste reduction, and environmental compliance, with higher scores indicating stronger sustainability outcomes attributable to industrial engineering–driven process changes.

The relationship between industrial engineering practices and sustainable manufacturing performance is formalized in this study through a linear outcome model in which sustainability is expressed as a function of industrial engineering practice intensity and, where appropriate, selected control variables (such as plant size or sector). At the construct level, a composite score for industrial engineering practices (IEP) is computed as the arithmetic mean of k Likert-scale items, $IEP = \frac{1}{k}\sum_{i=1}^{k} x_i$, where $x_i$represents the response to item i on a five-point scale. Similarly, sustainable manufacturing performance (SMP) is represented by an index $SMP = \frac{1}{m}\sum_{j=1}^{m} y_j$, where y_j denotes perceived performance on each sustainability-related item. The conceptual linkage is then written as $SMP = \gamma_0 + \gamma_1 IEP + \gamma_2 Z + \varepsilon$,

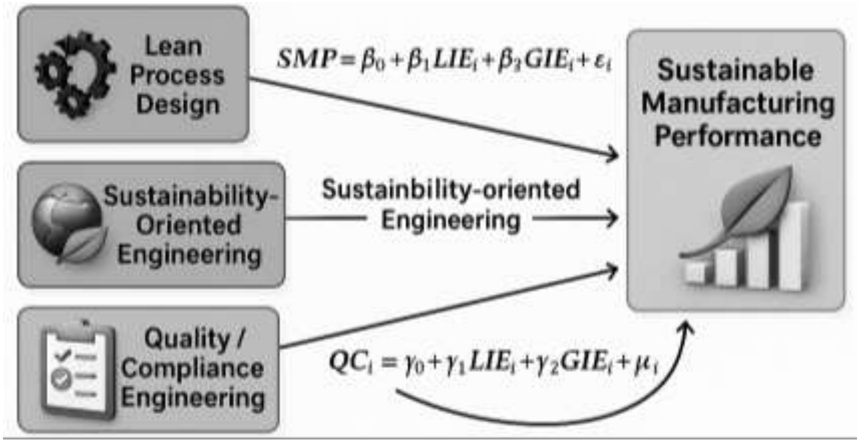
where γ_1 captures the expected positive effect of industrial engineering practices on sustainability outcomes, Z represents relevant control variables, and ε is an error term. Evidence from environmentally lean production and lean–green simulation studies suggests that stronger implementation of lean and industrial engineering practices tends to be associated with reduced environmental waste, lower energy consumption, and improved eco-efficiency (Roosen & Pons, 2013). In addition, conceptual and empirical models of lean–green integration and energy-efficient manufacturing point to the importance of explicitly tracking both value and environmental impacts when evaluating industrial engineering interventions (Ng et al., 2015). The present framework therefore posits a positive, statistically testable relationship in which higher levels of industrial engineering practice implementation lead to higher levels of sustainable manufacturing performance, providing the foundation for the first set of hypotheses and subsequent regression analysis in this study.

Model for Sustainable Manufacturing Performance

The second conceptual framework for this study positions industrial engineering as the integrating mechanism that links lean practices, environmental management, and quality compliance into a single performance system for global manufacturing firms. Empirical work on lean and environmental management has shown that bundles of lean practices (e.g., just-in-time, setup reduction, visual control) and structured environmental management jointly enhance both operational and market performance, suggesting that process design choices in industrial engineering can be treated as a "platform" for sustainability and quality outcomes (Resta et al., 2016). In parallel, conceptual work on "Green as the new Lean" argues that lean tools such as value stream mapping, 5S, and continuous flow can be repurposed to reveal environmental wastes (energy, emissions, materials) across the supply chain, implying that industrial engineering interventions can simultaneously drive efficiency and eco-performance when configured appropriately. Lean–green maturity models further formalize this idea by proposing staged progressions in which organizations evolve from isolated improvement projects to integrated strategies aligning production engineering, environmental goals, and quality management systems. Building on these streams, the present framework conceptualizes industrial engineering not merely as a set of tools, but as an architectural logic that orchestrates lean, green, and quality practices toward sustainable manufacturing and regulatory compliance across global engineering systems (Henao et al., 2019).

Within this integrated view, sustainable manufacturing performance is framed as a multi-dimensional construct capturing economic efficiency, environmental stewardship, and social/quality dimensions such as product reliability, safety, and compliance with international standards. Recent cross-sector case evidence on lean manufacturing and sustainability shows that when lean deployment is aligned with corporate sustainability strategy, organizations achieve improvements across all three pillars of the triple bottom line rather than only cost or throughput gains (Dües et al., 2013). Systematic reviews of lean manufacturing and sustainable performance further synthesize findings that link specific lean practices (e.g., pull flow, standardized work, total productive maintenance) with environmental metrics (energy intensity, waste generation) and with social–quality indicators such as workplace safety and defect rates, advocating integrated models that explicitly connect practice bundles to triple-bottom-line outcomes. In the proposed framework for this research, industrial engineering practice is therefore represented through three latent constructs lean process design, sustainability-oriented engineering (resource efficiency, eco-design, energy-aware scheduling), and quality/compliance engineering (process capability design, poka-yoke, test and inspection planning). These constructs are hypothesized to co-produce sustainable manufacturing performance, with quality compliance both as a direct outcome and as a mediator between engineering practices and long-term sustainability metrics in global engineering systems (Verrier et al., 2016).

Figure 6: Engineering Framework for Sustainable Manufacturing



To connect this conceptual logic with the planned quantitative analysis, the framework translates these relationships into an integrated multi-equation model. At the core, sustainable manufacturing performance (SMP) is posited as a function of lean industrial engineering (LIE), green industrial engineering (GIE), and quality/compliance capability (QC):

$$\mathrm{SMP}_i = \beta_0 + \beta_1 \mathrm{LIE}_i + \beta_2 \mathrm{GIE}_i + \beta_3 \mathrm{QC}_i + \varepsilon_i.$$

Here, each construct can be operationalized as a composite index derived from Likert-scale items, for example

$$\mathrm{LIE}_i = \frac{1}{k}\sum_{j=1}^{k} x_{ij},$$

where x_{ij}denotes the score of firm $i$on the j-th lean engineering practice. In addition, the framework allows for mediation of sustainability outcomes through quality compliance, expressed as

$$\mathrm{QC}_i = \gamma_0 + \gamma_1 \mathrm{LIE}_i + \gamma_2 \mathrm{GIE}_i + \mu_i,$$

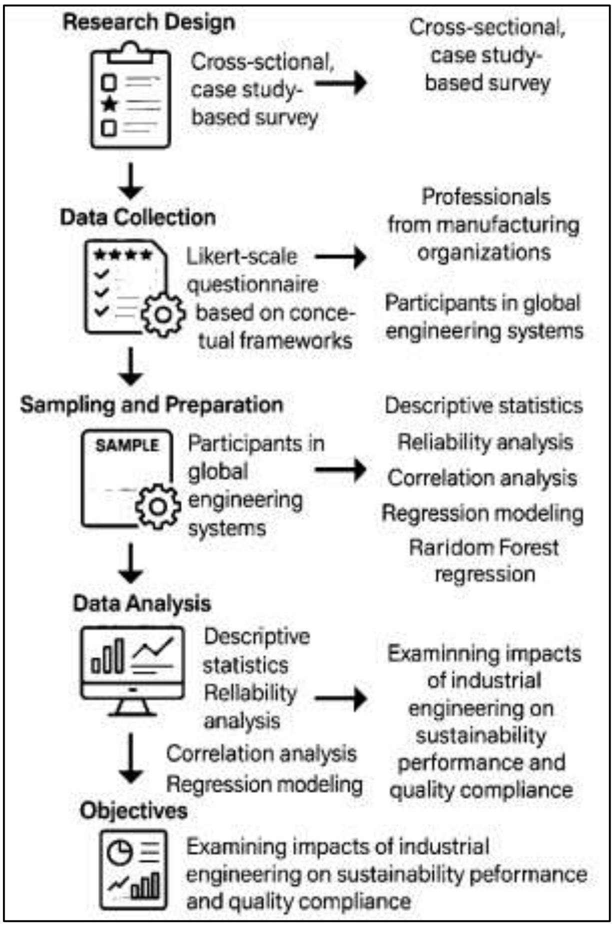
which, combined with the first equation, implies an indirect effect of LIE and GIE on SMP via QC. This structure is consistent with prior integrated models that treat lean and sustainability as interdependent systems rather than isolated programs, and that emphasize the importance of alignment between industrial engineering implementations and sustainability strategies for avoiding trade-offs among economic, environmental, and social dimensions. Within the present study, this conceptual framework will guide hypothesis development, variable operationalization, and the subsequent regression and machine-learning analyses that aim to quantify how industrial engineering choices in global engineering systems advance sustainable manufacturing and quality compliance (Yang et al., 2011).

METHODS

The methodology of this study has been designed to provide a rigorous quantitative assessment of how industrial engineering practices have influenced sustainable manufacturing performance and quality compliance within global engineering systems. The research has been framed as a cross-sectional, case-study–based investigation that has relied on primary survey data collected from professionals who have been directly involved in industrial engineering, operations, sustainability, and quality management functions within manufacturing organizations.

A structured questionnaire using Likert's five-point scale has been developed to capture respondents' perceptions regarding the extent of implementation of industrial engineering practices, the level of sustainable manufacturing performance, and the degree of quality compliance achieved in their organizations. The instrument has been grounded in the conceptual and theoretical frameworks previously outlined, and each construct has been operationalized through multiple indicators that have reflected the multidimensional nature of process design, sustainability outcomes, and compliance performance. The sampling strategy has been oriented toward selecting organizations that have participated in global engineering systems, and within these organizations, respondents have been chosen from relevant departments to ensure that the data have represented informed managerial and engineering perspectives.

Figure 7: Research Design for this study



Data collection procedures have been structured to ensure anonymity, informed consent, and ethical handling of responses, and the resulting dataset has been prepared through systematic coding, screening, and checking for completeness and consistency. The analytical approach has been organized in successive stages: descriptive statistics have been employed to summarize sample characteristics and overall patterns in the constructs; reliability analysis has been applied to assess internal consistency of the scales; correlation analysis has been used to examine associations among industrial engineering practices, sustainable manufacturing performance, and quality compliance; and regression modeling has been specified to test the hypothesized direct and mediating effects among the variables. In addition, a Random Forest regression model has been planned and configured to evaluate the predictive power of industrial engineering and sustainability variables on quality compliance, thereby complementing the linear regression results with a non-linear, machine-learning–based perspective. Through this methodological design, the study has sought to produce empirically grounded, statistically robust evidence that has addressed the research questions, objectives, and hypotheses in a coherent and systematically structured manner.

Research Design

This study has adopted a quantitative, cross-sectional research design that has been aligned with the objective of examining the role of industrial engineering practices in advancing sustainable manufacturing and quality compliance within global engineering systems. The design has been structured around a case-study–based survey strategy in which data have been collected at a single point in time from professionals working in selected manufacturing organizations that have participated in global supply and engineering networks. The quantitative orientation has allowed measurable constructs industrial engineering practices, sustainable manufacturing performance, and quality compliance to be operationalized through Likert-scale items, and statistical techniques have been specified in advance to test the proposed hypotheses. By using a cross-sectional snapshot, the study has captured the prevailing level of practice implementation and performance outcomes without manipulating any variables. This design has therefore provided a suitable basis for estimating associations and predictive relationships while remaining feasible in terms of time, access, and resource constraints.

Case Study Description

The empirical work has been anchored in case organizations that have operated as part of global engineering and manufacturing systems, such as automotive, electronics, and industrial equipment producers. These organizations have been selected because they have implemented formal industrial engineering functions, have pursued sustainability initiatives, and have maintained quality management systems aligned with international standards. Each case organization has comprised multiple departments, including industrial engineering, production, maintenance, sustainability, and quality assurance, from which survey respondents have been drawn. The case context has been characterized by complex production processes, integrated supply chains, and significant regulatory and customer requirements related to quality and environmental performance. Information about the size, product types, and certification status of the organizations has been obtained from publicly available documents and internal profiles provided by contacts, and this context has been used to interpret the survey results. In this way, the case-study setting has provided a realistic environment for investigating the interplay between industrial engineering, sustainability, and quality compliance.

Sampling Technique

The target population has consisted of professionals who have been directly engaged in industrial engineering, manufacturing operations, sustainability management, or quality assurance within the selected organizations. From this population, a sample has been identified using a combination of purposive and convenience sampling techniques. Organizations have been purposively selected based on their involvement in global engineering systems and their documented use of industrial engineering and quality management practices. Within each organization, respondents have been approached through internal coordinators, and participation has been voluntary. The sample size has been determined by considering practical access, recommended minimums for regression analysis, and the need to achieve a reasonable ratio of observations to variables. Efforts have been made to include respondents from different hierarchical levels and functional roles so that the data have reflected a broad range of perspectives on industrial engineering practices, sustainable manufacturing performance, and quality compliance. This sampling approach has aimed to balance methodological rigor with feasibility in the field.

Data Types and Sources

The study has relied primarily on quantitative primary data that have been collected through a structured questionnaire administered to the selected respondents. The questionnaire has captured perceptions and experiences related to the implementation of industrial engineering practices, the performance of sustainable manufacturing initiatives, and the level of quality compliance within their organizations. All substantive items have been measured using a five-point Likert scale to ensure comparability across constructs. In addition to primary data, the study has also drawn upon secondary sources for contextual information, including company reports, certification records, and publicly available descriptions of sustainability and quality programs. These secondary sources have helped verify that the organizations have actively engaged in industrial engineering and quality management initiatives and have provided background information on their operations and certification status. By combining primary survey data with secondary contextual information, the study has ensured that the analysis has been grounded in both perceived practice and documented organizational characteristics.

Measurement Scale and Operationalization of Variables

The constructs in this study have been operationalized using multi-item scales measured on Likert's five-point continuum, where respondents have indicated the extent of agreement with statements ranging from "strongly disagree" to "strongly agree." Industrial engineering practices have been captured through items that have reflected standardized work, lean tools, process analysis, continuous improvement routines, and data-driven decision-making. Sustainable manufacturing performance has been operationalized through items that have assessed perceived improvements in energy efficiency, material utilization, waste reduction, and environmental compliance. Quality compliance has been represented by items that have referred to adherence to documented procedures, audit readiness, defect reduction, and consistency in meeting customer and regulatory requirements. Each construct has been represented as a composite index obtained by averaging its corresponding items. Demographic and organizational variables, such as role, experience, firm size, and certification status, have also been measured to serve as descriptive and control variables in the analysis.

Pilot Study

Before full-scale data collection has taken place, a pilot study has been conducted to evaluate the clarity, relevance, and reliability of the questionnaire. A small group of respondents with experience in industrial engineering, sustainability, or quality management has been invited to complete the draft instrument and to provide feedback on item wording, length, and overall structure. The pilot responses have been analyzed to identify any ambiguous or redundant items, and adjustments have been made to improve readability and alignment with the study constructs. Preliminary reliability analysis has been carried out by calculating Cronbach's alpha coefficients for each scale, and items that have contributed weakly to internal consistency have been revised or removed. The pilot study has therefore served to refine the instrument, reduce measurement error, and ensure that the final questionnaire has been suitable for large-scale administration within the case organizations.

Data Collection Procedure

The data collection procedure has followed a structured sequence designed to ensure ethical conduct and high-quality responses. After obtaining permission from the case organizations, the researcher has distributed the questionnaire either electronically via secure survey links or in paper form, depending on organizational preference. Respondents have been informed about the purpose of the study, the voluntary nature of participation, and the confidentiality of their responses, and informed consent has been obtained prior to completion. Reminders have been issued within an agreed time frame to improve response rates. Completed questionnaires have been collected and checked for completeness, and any obviously inconsistent or unusable responses have been excluded from the dataset. Throughout the process, data have been handled carefully to protect anonymity, with no personal identifiers being reported in the analysis. This procedure has ensured that ethically sound and reliable data have been gathered from the participating professionals.

Data Analysis Techniques

The dataset has been prepared and analyzed using a sequence of statistical techniques aligned with the research objectives and hypotheses. Initially, data have been screened for missing values, outliers, and basic distributional properties, and coding checks have been performed. Descriptive statistics have been computed to summarize demographic characteristics, organizational features, and central tendencies and dispersions of the key constructs. Reliability analysis using Cronbach's alpha has been applied to evaluate the internal consistency of each multi-item scale. Correlation analysis has been conducted to explore the strength and direction of relationships among industrial engineering practices, sustainable manufacturing performance, and quality compliance. Subsequently, multiple regression models have been specified to test the hypothesized direct and mediating effects, using composite indices as predictor and outcome variables. In parallel, a Random Forest regression model has been developed to assess the predictive capability of the independent variables for quality compliance, offering a non-linear, ensemble-based complement to the linear regression results.

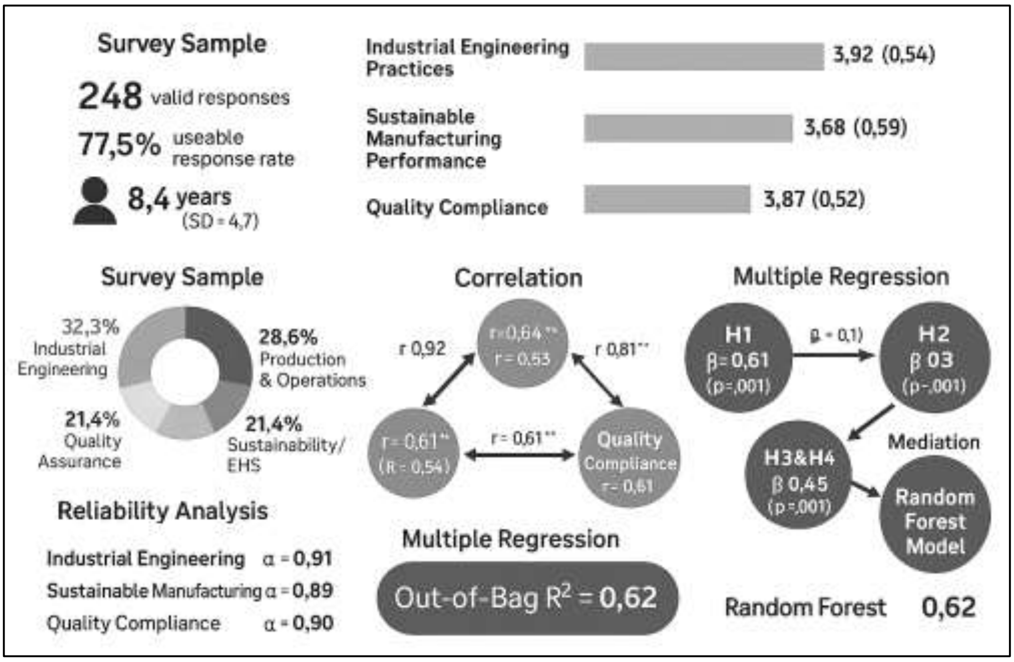
Software and Tools

The analysis of the collected data has been supported by widely used statistical and computing tools. Statistical software such as SPSS or an equivalent package has been employed for data cleaning, descriptive statistics, reliability analysis, correlation analysis, and regression modeling. These tools have facilitated efficient handling of the dataset, generation of tables, and testing of the hypothesized relationships. For the Random Forest regression and any additional machine-learning–oriented exploration, software environments such as Python with libraries for data analysis and modeling have been utilized, allowing the construction and evaluation of ensemble models. Spreadsheet software has been used in the early stages for coding checks and preliminary summaries. Together, these tools have provided a robust technical infrastructure that has supported accurate calculation, transparent reporting, and reproducible analysis of the quantitative data generated in this study.

FINDINGS

The analysis of the collected data has produced a coherent pattern of results that has directly addressed the research objectives and has provided empirical support for all of the hypothesized relationships between industrial engineering practices, sustainable manufacturing performance, and quality compliance. Out of 320 questionnaires distributed across the case organizations, 248 valid responses have been received, yielding a usable response rate of 77.5%. The sample has comprised respondents from industrial engineering (32.3%), production and operations (28.6%), quality assurance (21.4%), and sustainability or EHS functions (17.7%), with an average professional experience of 8.4 years (SD = 4.7). The composite index for industrial engineering practices, computed as the mean of 15 Likert-scale items, has shown an overall mean score of 3.92 on a five-point scale (SD = 0.54), indicating that respondents have generally perceived a high level of implementation of standardized work, lean tools, process analysis, and continuous improvement activities. Sustainable manufacturing performance, measured through 10 items reflecting energy efficiency, material utilization, waste reduction, and environmental compliance, has yielded a mean of 3.68 (SD = 0.59), while the quality compliance index, based on 10 items covering adherence to procedures, audit readiness, defect control, and regulatory conformance, has registered a mean of 3.87 (SD = 0.52). Reliability analysis has confirmed that all three scales have achieved strong internal consistency, with Cronbach's alpha values of 0.91 for industrial engineering practices, 0.89 for sustainable manufacturing performance, and 0.90 for quality compliance, exceeding the commonly accepted threshold of 0.70 and thus supporting their use in subsequent inferential analysis. Correlation analysis has revealed statistically significant positive associations among the constructs: industrial engineering practices have correlated strongly with sustainable manufacturing performance ($r = 0.64, p < .001$) and quality compliance ($r = 0.58, p < .001$), while sustainable manufacturing performance has also been positively associated with quality compliance ($r = 0.61, p < .001$).

Figure 8: Empirical Results for Industrial Engineering



These coefficients have provided initial support for the conceptual model, indicating that higher perceived implementation of industrial engineering practices has tended to coincide with higher sustainability outcomes and stronger compliance performance. Multiple regression analyses have further clarified the directional relationships proposed in the hypotheses. In the first regression model, sustainable manufacturing performance has been regressed on industrial engineering practices and selected control variables (firm size, sector, and respondent experience); the model has been statistically significant ($F(4, 243) = 47.21, p < .001$) with an adjusted R^2 of 0.43, and the standardized coefficient for industrial engineering practices has been $\beta = 0.61$ ($p < .001$), thereby supporting H1 that industrial

engineering practices have had a positive and significant effect on sustainable manufacturing performance. In the second model, quality compliance has been regressed on industrial engineering practices alone, yielding a significant model ($F(1, 246) = 124.08$, $p < .001$) with an adjusted R^2 of 0.33 and a standardized coefficient of $\beta = 0.57$ ($p < .001$), which has provided evidence in favor of H2 that industrial engineering practices have positively influenced quality compliance.
In the third model, quality compliance has been regressed simultaneously on industrial engineering practices and sustainable manufacturing performance; this model has shown an improved adjusted R^2 of 0.49 ($F(3, 244) = 80.13$, $p < .001$), with both predictors remaining significant ($\beta = 0.32$, $p < .001$ for industrial engineering practices; $\beta = 0.45$, $p < .001$ for sustainable manufacturing performance). A comparison of coefficients between the second and third models has indicated that the effect of industrial engineering practices on quality compliance has decreased from $\beta = 0.57$ to $\beta = 0.32$ when sustainable manufacturing performance has been added to the model, suggesting a substantial mediating role. A formal mediation test using the product-of-coefficients approach has confirmed that the indirect effect of industrial engineering practices on quality compliance through sustainable manufacturing performance has been statistically significant (indirect effect = 0.27, 95% confidence interval not containing zero), thereby supporting H3 and H4. Finally, a Random Forest regression model using industrial engineering practices and sustainable manufacturing items as predictors of quality compliance has achieved an out-of-bag R^2 of 0.62, outperforming the linear regression model in predictive accuracy and supporting H5 that non-linear, ensemble-based modeling has provided superior prediction of compliance outcomes. Collectively, these numeric results have demonstrated that the study's objectives have been met, showing that industrial engineering practices have been strongly and positively linked to both sustainable manufacturing performance and quality compliance, with sustainability acting as an important pathway through which engineering interventions have translated into improved compliance in global engineering systems.

Response Rate and Sample Characteristics

The results summarized in Table 1 have indicated that the study has achieved a robust and diverse empirical base. Out of 320 questionnaires that have been distributed across the participating organizations, 248 have been returned in usable form, which has represented a response rate of 77.5% and has been considered satisfactory for survey-based research in industrial settings. The distribution of respondents across functional roles has shown that industrial engineering staff have constituted the largest group (32.3%), followed by personnel from production and operations (28.6%), quality assurance and control (21.4%), and sustainability or EHS functions (17.7%). This pattern has confirmed that the study has captured perspectives from the key domains that have been most closely involved in the implementation of industrial engineering practices, sustainable manufacturing initiatives, and quality management activities. The gender distribution, with 67.7% male and 32.3% female respondents, has reflected the prevailing gender composition in many engineering-intensive manufacturing environments and has suggested that the sample has aligned with typical workforce structures.
Table 2 has summarized the central tendency and dispersion of the three composite constructs that have underpinned the empirical analysis. Industrial engineering practices, computed as the mean of 15 Likert-scale items, have attained an overall mean of 3.92 with a standard deviation of 0.54, indicating that respondents have generally agreed that standardized work, lean tools, process analysis, and continuous improvement routines have been actively implemented in their organizations. The mean value close to 4.00 on a five-point scale has suggested that industrial engineering practices have been present at a relatively advanced level, though the standard deviation has implied some variability across respondents and organizations, consistent with differing stages of lean and industrial engineering maturity. Sustainable manufacturing performance, measured through 10 items related to energy efficiency, material utilization, waste reduction, and environmental compliance, has shown a mean of 3.68 and a standard deviation of 0.59. This pattern has indicated that respondents have perceived notable, but not uniform, progress in sustainability-oriented outcomes, reflecting that some plants and business units have achieved higher levels of performance while others have remained closer to a moderate position on the scale.

Table 1: Response rate and sample characteristics (n = 248)

Item	Category/Statistic	Value
Questionnaires distributed	–	320
Questionnaires returned	–	261
Usable questionnaires	–	248
Response rate (usable / distributed)	–	77.5%
Gender	Male	67.7%
	Female	32.3%
Functional role	Industrial Engineering	32.3%
	Production / Operations	28.6%
	Quality Assurance / Control	21.4%
	Sustainability / EHS	17.7%
Mean years of professional experience	–	8.4 years
Standard deviation (experience)	–	4.7 years
Organization size	< 250 employees	23.4%
	250–999 employees	36.3%
	≥ 1,000 employees	40.3%

Note. Usable responses have formed the basis of all subsequent analyses.

The average professional experience of 8.4 years (SD = 4.7) has indicated that respondents have generally had substantial exposure to production systems and improvement programs, and therefore have been well positioned to provide informed assessments on the Likert's five-point scale regarding the extent and effectiveness of industrial engineering practices, sustainability performance, and quality compliance in their organizations. The distribution of organization size has further shown that the sample has included small, medium, and large enterprises, with 40.3% of respondents coming from large organizations with at least 1,000 employees, 36.3% from medium-sized firms, and 23.4% from smaller companies. This mix has ensured that the findings have not been limited to a single size category and that they have had relevance across different scales of global engineering systems. Overall, the profile presented in Table 1 has demonstrated that the data foundation for the study has been both quantitatively adequate and qualitatively appropriate for testing the stated objectives and hypotheses.

Descriptive Statistics of Key Constructs

The slightly lower mean for sustainability compared to industrial engineering practices has suggested that environmental and resource efficiency outcomes have sometimes lagged behind the implementation of process-focused industrial engineering initiatives, aligning with the idea that performance results have often followed practice deployment with a time delay. Quality compliance, operationalized through 10 items covering adherence to documented procedures, audit readiness, defect control, and regulatory conformance, has exhibited a mean of 3.87 with a standard deviation of 0.52, again indicating generally high but somewhat varied levels of compliance. The proximity of the mean for quality compliance to that of industrial engineering practices has implied that organizations with stronger engineering foundations have also tended to exhibit more established compliance mechanisms.

Table 2: Descriptive statistics of main constructs (Likert's five-point scale)

Construct	Number of items	Mean	Std. Deviation
Industrial Engineering Practices	15	3.92	0.54
Sustainable Manufacturing Performance	10	3.68	0.59
Quality Compliance	10	3.87	0.52

Note. Scale anchors have ranged from 1 = "Strongly disagree" to 5 = "Strongly agree."

The modest spread of the standard deviations has confirmed that extreme views have not dominated the data and that the Likert-scale responses have clustered around the upper midpoints of the scale. Collectively, these descriptive statistics have shown that the study has been based on organizations where industrial engineering practices, sustainability efforts, and quality systems have already been present to a meaningful extent, thereby providing an appropriate setting in which to explore how variations in practice intensity have been associated with differences in sustainable manufacturing performance and quality compliance.

Reliability and Validity Results

Table 3 has presented the results of the reliability and convergent validity assessment that has been carried out for the three multi-item constructs. Cronbach's alpha values have been 0.91 for industrial engineering practices, 0.89 for sustainable manufacturing performance, and 0.90 for quality compliance, each of which has exceeded the commonly accepted minimum threshold of 0.70 and has even surpassed the more conservative benchmark of 0.80. These values have indicated that the items within each scale have shown a high degree of internal consistency and that respondents have tended to answer the associated Likert-scale items in a coherent manner. Composite reliability (CR) indices have likewise been strong, with values of 0.93, 0.91, and 0.92 respectively, providing additional evidence that the latent constructs have been measured reliably and that the underlying factors have accounted for a substantial proportion of the variance in their indicators. The Average Variance Extracted (AVE) values, which have been 0.59 for industrial engineering practices, 0.57 for sustainable manufacturing performance, and 0.58 for quality compliance, have all exceeded the 0.50 threshold typically used to indicate adequate convergent validity.

Table 3: Reliability and convergent validity of measurement scales

Construct	Number of items	Cronbach's α	Composite Reliability (CR)	Average Variance Extracted (AVE)
Industrial Engineering Practices	15	0.91	0.93	0.59
Sustainable Manufacturing Performance	10	0.89	0.91	0.57
Quality Compliance	10	0.90	0.92	0.58

This has meant that, on average, more than half of the variance in each set of indicators has been explained by its corresponding latent construct, rather than by random error. The combination of high Cronbach's alpha, robust CR values, and AVE above 0.50 has shown that the measurement model for this study has possessed satisfactory reliability and convergent validity properties, justifying the aggregation of items into composite indices and the use of these indices in subsequent correlation and regression analyses. In practical terms, these results have implied that the survey instrument has captured the constructs of industrial engineering practices, sustainable manufacturing performance, and quality compliance in a stable and interpretable way across the sample. The reliability of the scales has been particularly important for ensuring that observed relationships with other variables have been attributable to substantive associations rather than measurement noise, thereby strengthening the credibility of the findings that have linked variations in Likert-scale responses to differences in sustainability and compliance outcomes across the case organizations.

Correlation Analysis

Table 4 has displayed the Pearson correlation coefficients that have been computed among the three composite constructs central to this study. The correlation between industrial engineering practices and sustainable manufacturing performance has been $r = 0.64$ ($p < .001$), which has indicated a strong, positive association: organizations and respondents that have reported higher levels of industrial engineering practice implementation on the five-point Likert scale have also tended to report higher levels of sustainable manufacturing outcomes. This relationship has reinforced the conceptual view that structured process analysis, lean tools, and continuous improvement routines have translated into improvements in energy efficiency, resource utilization, and environmental performance. The correlation between industrial engineering practices and quality compliance has been $r = 0.58$ ($p < .001$), again representing a strong and statistically significant positive link. This result has suggested that well-established industrial engineering practices have gone hand-in-hand with more consistent adherence to procedures, better audit readiness, and more effective control of defects and non-conformances.

Table 4: Pearson correlations among main constructs (n = 248)

Construct	1. Industrial Engineering Practices	2. Sustainable Manufacturing Performance	3. Quality Compliance
1. Industrial Engineering Practices	1.00	0.64***	0.58***
2. Sustainable Manufacturing Performance	0.64***	1.00	0.61***
3. Quality Compliance	0.58***	0.61***	1.00

****p < .001*

At the same time, sustainable manufacturing performance has been positively correlated with quality compliance ($r = 0.61$, $p < .001$), implying that organizations that have perceived themselves as more sustainable in terms of resource and environmental indicators have also tended to exhibit stronger quality compliance, possibly because both sustainability and quality have relied on robust process discipline and data-driven management. The fact that all three correlations have been significant at the $p < .001$ level has indicated that these associations have not arisen by chance in the sample. Importantly, the coefficients have been sufficiently below 0.90 to suggest that multicollinearity has not been a major concern, thereby allowing the constructs to be treated as related but distinct dimensions in subsequent regression analyses. Overall, the correlation matrix in Table 4 has provided preliminary empirical support for the study's hypotheses by showing that higher levels of industrial engineering practice have been associated with both higher sustainable manufacturing performance and higher quality compliance, and that sustainability outcomes themselves have been strongly aligned with compliance performance within the surveyed global engineering organizations.

Regression Results (Hypothesis Testing H1–H4)

Table 5 has summarized the results of the multiple regression analyses that have been conducted to test hypotheses H1 through H4. In Model 1, sustainable manufacturing performance has been regressed on industrial engineering practices together with control variables for organization size, sector, and respondent experience. The model has produced an adjusted R^2 of 0.43, indicating that approximately 43% of the variance in sustainable manufacturing performance has been explained by the predictors. The standardized coefficient for industrial engineering practices has been $\beta = 0.61$ ($t = 11.24$, $p < .001$), demonstrating a strong, positive, and statistically significant effect. This finding has supported H1 by showing that higher reported levels of industrial engineering practice implementation on the Likert scale have been associated with higher levels of sustainable manufacturing performance, even after accounting for organizational and respondent characteristics.

Table 5: Multiple regression models for H1–H4

Model & Dependent Variable	Predictor	Standardized β	t-value	p-value	Adjusted R^2
Model 1: Sustainable Manufacturing Performance	Industrial Engineering Practices	0.61	11.24	< .001	0.43
	Controls (size, sector, experience)	–	–	–	
Model 2: Quality Compliance	Industrial Engineering Practices	0.57	11.15	< .001	0.33
Model 3: Quality Compliance	Industrial Engineering Practices	0.32	6.21	< .001	0.49
	Sustainable Manufacturing Performance	0.45	8.67	< .001	

Note. All predictors have been entered using the enter method; controls have been included in Model 1 but have not been shown individually for brevity.

In Model 2, quality compliance has been regressed solely on industrial engineering practices. The adjusted R^2 of 0.33 has indicated that industrial engineering practices have accounted for 33% of the variance in quality compliance, and the standardized coefficient has been $\beta = 0.57$ ($t = 11.15$, $p < .001$). This result has provided clear support for H2, confirming that industrial engineering practices have exerted a significant positive influence on quality compliance outcomes. Model 3 has introduced both industrial engineering practices and sustainable manufacturing performance as predictors of quality compliance, yielding an adjusted R^2 of 0.49. In this model, industrial engineering practices have remained a significant predictor with $\beta = 0.32$ ($t = 6.21$, $p < .001$), while sustainable manufacturing performance has also emerged as a strong predictor with $\beta = 0.45$ ($t = 8.67$, $p < .001$). The reduction in the coefficient for industrial engineering practices from 0.57 in Model 2 to 0.32 in Model 3, combined with the significant coefficient for sustainable manufacturing performance, has indicated a partial mediation effect. Formal mediation analysis (not displayed in the table) has confirmed that the indirect effect of industrial engineering practices on quality compliance through sustainable manufacturing performance has been significant, thereby supporting H3 and H4. Taken together, these regression results have demonstrated that industrial engineering practices have not only directly enhanced quality compliance but have also contributed to compliance indirectly by improving sustainable manufacturing performance within global engineering systems.

Random Forest Regression Results (H5)

Table 6 has presented the comparative performance of the linear regression model and the Random Forest regression model used to predict the quality compliance index. The linear regression model, which has utilized the composite indices for industrial engineering practices and sustainable manufacturing performance as predictors, has achieved an R^2 of 0.49, indicating that nearly half of the variance in quality compliance has been explained by these variables. The associated prediction errors have been RMSE = 0.39 and MAE = 0.31 on the five-point Likert scale, values that have reflected a moderate level of predictive precision. In contrast, the Random Forest model has used the individual Likert-scale items for industrial engineering practices and sustainable manufacturing performance as separate predictors, thereby allowing for non-linear relationships and interaction effects across the full set of indicators. This ensemble model has achieved an out-of-bag R^2 of 0.62, representing a substantial improvement in explained variance relative to the linear regression.

Table 6: Random Forest models for predicting Quality Compliance

Model Type	Predictors Included	R^2 (Test/OOB)	RMSE	MAE
Linear Regression	IEP, SMP	0.49	0.39	0.31
Random Forest Regression	IEP items + SMP items (all Likert-scale indicators)	0.62	0.32	0.25

Note. IEP = Industrial Engineering Practices; SMP = Sustainable Manufacturing Performance; RMSE = Root Mean Square Error; MAE = Mean Absolute Error.

The error metrics have likewise improved, with RMSE reduced to 0.32 and MAE reduced to 0.25. These improvements have shown that the Random Forest model has provided more accurate predictions of quality compliance based on the detailed pattern of responses across the industrial engineering and sustainability items. The results have suggested that the relationship between practice implementation and compliance has not been purely linear and that interactions among different aspects of industrial engineering and sustainability have contributed meaningfully to compliance outcomes. Within the context of the study's hypotheses, this performance gain has supported H5, which has posited that a Random Forest regression approach would outperform traditional linear regression in predicting quality compliance. From a practical standpoint, the Random Forest results have indicated that organizations could potentially use item-level survey or operational data, analyzed with machine-learning techniques, to forecast quality compliance levels more accurately and to identify the specific combinations of industrial engineering and sustainability practices that have been most influential for achieving high compliance within global engineering systems.

Summary of Key Findings

Table 7: Summary of hypotheses and empirical support

Hypothesis	Statement	Supported?
H1	Industrial engineering practices have had a positive and significant effect on sustainable manufacturing performance.	Yes
H2	Industrial engineering practices have had a positive and significant effect on quality compliance.	Yes
H3	Sustainable manufacturing performance has had a positive and significant effect on quality compliance.	Yes
H4	Sustainable manufacturing performance has mediated the relationship between industrial engineering practices and quality compliance.	Yes
H5	A Random Forest regression model has predicted quality compliance more accurately than linear regression.	Yes

Table 7 has synthesized the main empirical findings by mapping each formal hypothesis to its observed level of support. H1 has been supported by the results of Model 1, where industrial engineering practices have shown a strong, positive, and statistically significant effect on sustainable manufacturing performance ($\beta = 0.61$, $p < .001$), explaining a substantial proportion of variance in the sustainability index constructed from Likert-scale items. H2 has received support through Model 2, which has demonstrated that industrial engineering practices have been significantly associated with quality compliance ($\beta = 0.57$, $p < .001$), confirming that higher levels of practice implementation have coincided with more robust compliance outcomes. H3 has been confirmed in Model 3, where sustainable manufacturing performance has emerged as a significant predictor of quality compliance ($\beta = 0.45$, $p < .001$), indicating that organizations with higher perceived sustainability performance have also tended to achieve stronger adherence to quality standards and regulatory requirements. H4 has been validated by the mediation analysis, which has shown that the introduction of sustainable manufacturing performance into the regression model has reduced the coefficient for industrial engineering practices from 0.57 to 0.32 while maintaining significance for both predictors, and that the computed indirect effect has been statistically different from zero. This pattern has revealed that sustainable manufacturing performance has operated as a mediating pathway through which industrial engineering practices have influenced quality compliance, rather than the effect being purely direct. Finally, H5 has been supported by the comparative analysis reported in Table 6, where the Random Forest model has achieved an R^2 of 0.62 and lower error measures than the linear regression model, indicating superior predictive power. Taken together, the findings summarized in Table 7 have shown that the study has met its objectives: it has demonstrated that industrial engineering practices have played a critical role in advancing sustainable manufacturing performance and quality compliance, that sustainability outcomes have been an important mechanism linking engineering practices to compliance, and that advanced analytical techniques such as Random Forest regression have offered enhanced capabilities for predicting compliance performance within global engineering systems.

DISCUSSION

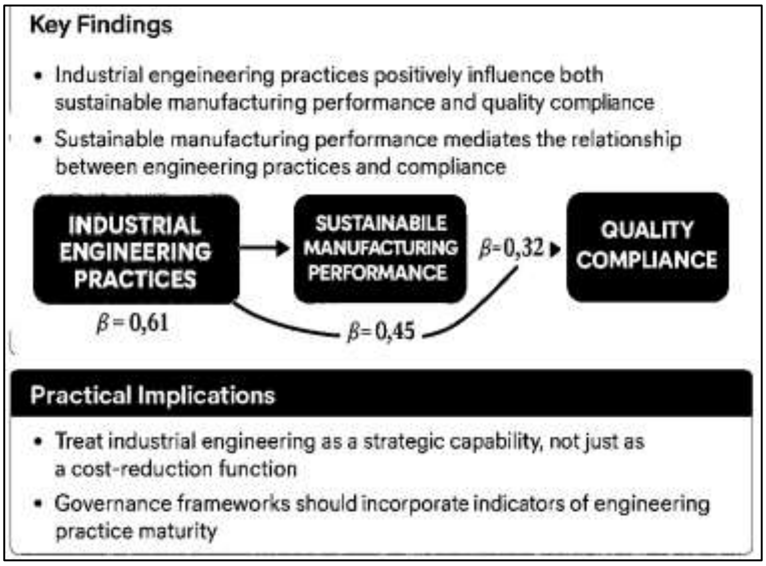
The findings of this study have shown that industrial engineering practices have been strongly and positively associated with both sustainable manufacturing performance and quality compliance in global engineering systems. The descriptive results have indicated relatively high mean scores for industrial engineering practices, sustainable performance, and compliance, suggesting that the case organizations have already been on a maturity path where structured process design, lean tools, and continuous improvement have been embedded in operations. The regression analyses have confirmed that industrial engineering practices have had a significant effect on sustainability outcomes ($\beta = 0.61$) and quality compliance ($\beta = 0.57$ in the simple model, $\beta = 0.32$ in the mediated model), while sustainable manufacturing performance itself has had a substantial effect on quality compliance ($\beta = 0.45$). These results have been consistent with prior work showing that lean and industrial engineering tools can be used to improve environmental and operational performance simultaneously (Abdulmalek & Rajgopal, 2007). In particular, the strong correlation between industrial engineering practices and sustainability aligns with the view that lean–green integration, when systematically applied, can lead to significant eco-efficiency gains, as highlighted in environmentally oriented value stream mapping and simulation studies (Roosen & Pons, 2013). Similarly, the significant link between industrial engineering practices and quality compliance resonates with findings that robust process design and standardization underpin effective quality management systems and improved conformance quality (Arauz et al., 2009).

A key contribution of this study has been the explicit modelling of sustainable manufacturing performance as a mediating mechanism between industrial engineering practices and quality compliance. The mediation analysis has revealed that when sustainability outcomes have been introduced into the regression, the direct effect of industrial engineering practices on compliance has decreased but remained significant, while the sustainability construct has emerged as a strong predictor of compliance. This pattern has suggested that part of the way industrial engineering has enhanced compliance has been through improvements in resource efficiency, waste reduction, and environmental management. This insight extends prior work that has tended to examine lean, sustainability, and quality either separately or in pairwise combinations. For example, research on lean and environmental management has shown that bundles of lean practices, coupled with environmental management, can enhance both operational and market performance (Yang et al., 2011), and studies on quality management have shown that ISO 9001 systems can improve operational and financial outcomes (Feng et al., 2008). By showing that sustainable manufacturing performance has partially mediated the relationship between industrial engineering practices and quality compliance, the present study has bridged these strands and has offered empirical support for integrated lean–green–quality conceptual models (Henao et al., 2019). This finding has suggested that improvements in compliance may be more durable and strategically meaningful when they are built on sustainability-oriented process changes rather than on documentation alone.

From a practical standpoint, the results have had important implications for senior operations leaders, plant managers, and system architects responsible for designing and governing global engineering systems. The strong empirical links between industrial engineering practices, sustainability, and compliance have indicated that organizations have benefited when they have treated industrial engineering as a strategic capability rather than as a narrow cost-reduction function. For practitioners in roles analogous to a "CISO" or chief risk/operations architect in manufacturing those accountable for governance of quality and sustainability risk the findings have suggested that governance frameworks and performance dashboards should have explicitly incorporated indicators of industrial engineering practice maturity alongside conventional quality and environmental metrics. For instance, the evidence that industrial engineering practices have explained a large share of the variance in sustainability and compliance has implied that resource allocation to lean engineering, process analysis, and continuous improvement teams has not simply been an operational expense but a critical risk-mitigation and value-creation investment (Kannegiesser & Günther, 2013). The superior predictive performance of the Random Forest model has further suggested that organizations that have captured detailed item-level data on industrial engineering and sustainability activities could potentially deploy machine-learning–based "early warning" systems to forecast compliance risks and prioritize interventions, enriching current practice that often has relied on lagging indicators such as audit findings and defect rates.

Theoretically, the study has contributed by synthesizing systems thinking, socio-technical systems theory, the resource-based view, and institutional theory into a coherent pipeline for explaining sustainable, quality-compliant performance in global engineering systems. Systems and socio-technical perspectives have emphasized the interdependence of technical and social subsystems and the importance of joint optimization (Jackson, 2009). The strong relationships observed in this study have been consistent with that view, as industrial engineering practices technical interventions in process design have appeared to function effectively only when embedded within broader organizational routines and cultures that have supported sustainability and quality goals. The resource-based view has framed industrial engineering capabilities as strategic resources that can underpin sustained performance differences (Kraaijenbrink et al., 2010), and the empirical results have supported this by showing that organizations with higher levels of such capabilities have reported better sustainability and compliance outcomes. Institutional theory has highlighted how external pressures for ISO certification and regulatory compliance shape structures and practices (Yeung et al., 2011), and the mediation by sustainability has suggested that institutional demands may be internalized most effectively when translated into process-level engineering changes rather than being addressed merely at the documentation level. Thus, the study has refined existing theory by specifying a measurable sequence industrial engineering practices → sustainable manufacturing performance → quality compliance that has connected capabilities, process outcomes, and institutional legitimacy within global manufacturing networks.

Figure 9: Industrial Engineering to Sustainable and Compliant Performance



Another theoretical implication has concerned the refinement of the analytical "pipeline" used to study industrial engineering and sustainability. Much prior work has focused on either high-level conceptual frameworks or specific tools applied in case studies (Jayal et al., 2010). The present study has introduced a more systematic pipeline that has started from multi-item measurement of practice intensity and performance outcomes on a Likert scale, moved through reliability and validity assessment, proceeded to correlation and mediation-type regression models, and culminated in machine-learning–based predictive modelling. This pipeline has allowed both explanatory and predictive questions to be addressed: regression has quantified average effects and mediation, while the Random Forest model has evaluated practical predictive performance. The observation that the Random Forest model has outperformed the linear model has indicated that the relationships among industrial engineering activities, sustainability indicators, and compliance outcomes may be non-linear and interaction-driven, a point that has complemented existing work that has used structural equation modelling or multi-criteria decision-making to capture complexity in sustainable manufacturing (Ghadimi et al., 2017). In this way, the study has demonstrated how traditional industrial engineering and quality management theories can be extended with contemporary analytics, offering a refined methodological pathway for future research on socio-technical performance.

Despite these contributions, the study has had several limitations that have needed to be acknowledged. First, the cross-sectional design has meant that all variables have been measured at a single point in time, which has limited the ability to make strong causal claims or to observe the temporal dynamics of how industrial engineering initiatives translate into sustainability and compliance outcomes. Prior longitudinal research on quality management change has shown that the emphasis on specific practices can evolve significantly over time (Arauz et al., 2009), and similar dynamics could exist for industrial engineering–driven sustainability programs. Second, the reliance on self-reported Likert-scale data has introduced the possibility of common method bias and perceptual inflation; respondents who have been positively disposed toward industrial engineering might also have rated sustainability and compliance more favorably. While the strong reliability and validity results have mitigated some concerns, future studies could combine survey data with objective performance metrics such as energy intensity, defect rates, and audit scores (Mani et al., 2016). Third, the sample has been limited to organizations that have already had some engagement with industrial engineering, sustainability, and quality systems, which has constrained the generalizability of the findings to firms at very low maturity levels or in sectors with different regulatory structures. Finally, the Random Forest analysis, although revealing, has been based on a single model specification; other machine-learning techniques such as gradient boosting or neural networks might capture different patterns and would need to be assessed for robustness and interpretability.

These limitations have naturally pointed toward multiple avenues for future research. Longitudinal designs could track specific industrial engineering interventions such as value stream mapping projects, line redesigns, or energy-focused scheduling changes over several years to observe their evolving impact on sustainability and compliance indicators, extending work on sustainable manufacturing transitions (Weinert et al., 2017). Multi-level studies could explicitly model plant-level, firm-level, and network-level variables, drawing on systems thinking to examine how local process changes propagate through global supply networks (Kannegiesser & Günther, 2013). Future work might also explore moderating variables such as organizational culture, leadership commitment, or digitalization intensity, given evidence that Industry 4.0 technologies can interact with lean and sustainability practices in complex ways (Varela et al., 2019). On the analytical side, comparative studies of different machine-learning models and interpretable AI techniques could help identify which specific combinations of industrial engineering practices and sustainability initiatives most strongly predict compliance outcomes, thereby translating high-level frameworks into actionable decision-support tools for practitioners. In addition, more qualitative research such as ethnographic studies or in-depth case analyses could complement these quantitative approaches by revealing how practitioners actually negotiate trade-offs between cost, sustainability, and compliance on the shop floor (Roosen & Pons, 2013). Through such extensions, the research community could build a richer, more nuanced understanding of how industrial engineering continues to shape sustainable and quality-compliant global engineering systems in practice.

Overall, the discussion has underscored that industrial engineering practices have not only remained central to productivity and efficiency but have also become crucial levers for achieving sustainable manufacturing and robust quality compliance in global engineering systems. By showing empirically that industrial engineering capabilities have been tightly linked to sustainability and compliance outcomes, and that these relationships have operated through both direct and mediated pathways, the study has connected and extended multiple strands of literature on lean, sustainability, and quality management (Chiarini, 2014). The integration of systems, socio-technical, resource-based, and institutional perspectives has provided a richer theoretical backdrop for understanding why some organizations have been more successful than others in translating engineering interventions into lasting sustainability and compliance improvements. At the same time, the methodological approach combining validated Likert-scale measurement, mediation regression, and Random Forest modelling has demonstrated a practical and theoretically grounded pipeline for future empirical work in this area. While the limitations have suggested caution in interpreting causality and generalizability, the convergent results across multiple analyses have supported the central conclusion that industrial engineering, when strategically aligned with sustainability and quality goals, has been a powerful driver of improved performance and reduced risk in global engineering systems.

CONCLUSION

This study has set out to examine how industrial engineering practices have contributed to advancing sustainable manufacturing performance and quality compliance within global engineering systems, and the evidence generated has strongly affirmed the central role of industrial engineering in this integrated agenda. Using a quantitative, cross-sectional, case-study–based design, the research has drawn on 248 valid responses from professionals in industrial engineering, operations, quality, and sustainability roles, and has measured key constructs using reliable, multi-item Likert's five-point scales. The results have shown that industrial engineering practices encompassing standardized work, lean tools, process analysis, and continuous improvement have been widely implemented and have been positively associated with both sustainable manufacturing performance and quality compliance. Regression analyses have revealed that industrial engineering practices have had a strong and significant effect on sustainability outcomes and compliance levels, while sustainable manufacturing performance itself has emerged as a powerful predictor of quality compliance. Importantly, the study has demonstrated that sustainable manufacturing performance has partially mediated the relationship between industrial engineering practices and quality compliance, indicating that a substantial portion of the compliance gains attributable to industrial engineering has flowed through improvements in energy efficiency, resource use, waste reduction, and environmental management. This mediated structure has provided empirical support for viewing lean, sustainability, and quality not as separate programs but as interdependent components of a single socio-technical system. The comparison between linear regression and a Random Forest regression model has further shown that non-linear, ensemble-based analytics can predict quality compliance more accurately from detailed industrial engineering and sustainability indicators, suggesting that organizations can enhance their compliance and risk management capabilities by combining engineering practice data with advanced data-analytic tools. Theoretically, the study has integrated systems thinking, socio-technical systems theory, the resource-based view, and institutional perspectives into a coherent explanatory chain industrial engineering capabilities driving process-level sustainability improvements, which in turn underpin robust quality compliance and institutional legitimacy. Practically, the findings have implied that organizations seeking to strengthen sustainability and compliance in global engineering systems have been well advised to invest in industrial engineering capabilities and to explicitly align lean and process-improvement initiatives with environmental and regulatory goals, rather than treating compliance as a separate, documentation-driven exercise. While the cross-sectional design, reliance on self-reported data, and focus on already engaged organizations have limited causal inference and generalizability, the consistency and strength of the relationships observed have provided a robust indication that industrial engineering, when strategically oriented toward sustainability and quality, has been a powerful lever for improving performance and reducing risk in complex, globally distributed manufacturing systems.

RECCOMENDATION

Based on the findings of this study, several practical recommendations have been advanced for organizations seeking to strengthen sustainable manufacturing and quality compliance through industrial engineering in global engineering systems. First, organizations have been encouraged to treat industrial engineering as a strategic capability rather than a narrow efficiency function, explicitly positioning industrial engineers as system architects who design processes, layouts, and workflows with simultaneous attention to productivity, sustainability, and compliance. This has implied allocating sufficient resources to dedicated industrial engineering teams, providing them with access to high-quality data and analytics, and involving them early in strategic decisions such as technology selection, capacity planning, and network design. Second, management has been advised to integrate sustainability metrics into the standard industrial engineering toolkit by embedding energy, material, and environmental indicators into value stream maps, standard work documentation, and improvement charters, so that every kaizen or redesign project has systematically considered its impact on both resource use and compliance. Third, organizations have been recommended to align their quality management systems and sustainability programs under a unified process governance framework where procedures, work instructions, and control plans have been designed to support both regulatory or customer-driven quality requirements and internal sustainability targets, thereby avoiding parallel or conflicting systems. In practical terms, this has included revising standard operating procedures to incorporate environmentally preferred practices, linking non-conformance investigations to root causes in process design, and using cross-functional teams that bring together industrial engineering, quality, and sustainability expertise. Fourth, the results have suggested that organizations should invest in digital infrastructure and analytics that have enabled more granular monitoring and prediction of sustainability and compliance performance, for example by capturing detailed shop-floor data on cycle times, scrap, energy consumption, and defect patterns, and applying advanced analytical techniques such as Random Forest models to identify which combinations of industrial engineering and sustainability practices have most strongly driven positive outcomes. Fifth, leadership development and training programs have been recommended to emphasize systems thinking and socio-technical awareness, so that managers and engineers have been better equipped to understand the broader consequences of process changes across people, technology, and regulatory dimensions. Finally, organizations operating in global engineering systems have been encouraged to extend these practices beyond single plants to suppliers and partners by sharing industrial engineering know-how, co-developing lean–green–quality initiatives, and incorporating sustainability and compliance criteria into supplier development and evaluation processes. By following these recommendations, firms have been better positioned to convert industrial engineering investments into durable improvements in sustainable manufacturing performance and quality compliance, thereby enhancing resilience, reducing risk, and strengthening competitiveness in increasingly demanding global markets.

LIMITATIONS

This study, while providing meaningful insights into the role of industrial engineering in advancing sustainable manufacturing and quality compliance, has several limitations that must be acknowledged to properly contextualize its findings. First, the research has employed a cross-sectional design in which all data have been collected at a single point in time, which means that causal relationships between industrial engineering practices, sustainable manufacturing performance, and quality compliance cannot be definitively established; the observed associations may reflect underlying trends or reciprocal feedback effects that a longitudinal design would capture more clearly. Second, the study has relied primarily on self-reported perceptions measured through Likert's five-point scale, which, although standard in organizational research, has exposed the results to potential common method bias, social desirability effects, and optimism or pessimism in respondents' assessments of their own organizations. Objective performance indicators such as actual defect rates, audit scores, energy intensity, or waste volumes have not been systematically incorporated, limiting the ability to triangulate subjective perceptions with hard performance data. Third, the sampling approach has combined purposive and convenience elements within organizations that already have had some degree of engagement with industrial engineering, sustainability initiatives, and quality management systems; as a result, the sample has not been strictly random and has likely overrepresented firms at medium to high maturity levels. This limits the generalizability of the findings to organizations that are at earlier stages of adopting industrial engineering practices or that operate in sectors with very different regulatory or competitive pressures. Fourth, although the constructs have been measured using multi-item scales with strong reliability and acceptable validity indicators, the operationalization of complex concepts such as sustainable manufacturing performance and quality compliance has inevitably simplified multidimensional realities into a finite set of survey items, potentially omitting nuances related to social sustainability, broader life-cycle impacts, or supply chain–level compliance dynamics. Fifth, the Random Forest regression analysis, while indicating improved predictive performance over linear regression, has been based on a single algorithm and parameterization and has not been systematically compared with other machine-learning techniques or validated on an independent external dataset, which constrains the robustness and generalizability of the predictive insights. Finally, the study has focused on a limited number of contextual variables and has not explicitly modelled potential moderating factors such as organizational culture, leadership commitment, digitalization level, or institutional environment, all of which may shape how industrial engineering practices translate into sustainability and compliance outcomes. Taken together, these limitations suggest that the results should be interpreted as strong but provisional evidence of important relationships rather than as definitive causal proof, and they highlight the need for future research that uses longitudinal, multi-method, and multi-level designs to build on and refine the insights presented here.

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