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Advancing Green Industrial Systems in the Era of Industry 4.0/5.0: A Comprehensive Review and Strategic Framework

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ABSTRACT

Green Industrial Systems (GIS) embody an integrated paradigm that merges sustainable practices, advanced digital technologies, and strategic management to enhance environmental performance, resource efficiency, and socio-economic resilience. While previous research has explored clean production, circular economy models, and Industry 4.0/5.0 technologies, few studies have synthesized these dimensions into a unified GIS framework that effectively aligns technological innovation, human-centricity, and operational excellence.

This study presents a systematic literature review (SLR) of peer-reviewed publications from 2015 to 2025. Findings reveal that Industry 4.0 technologies—such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, digital twins, and additive manufacturing—significantly enhance energy efficiency, predictive maintenance, waste reduction, and circular operations. In parallel, Industry 5.0 principles advance human-centric design, ethical engineering, and social value creation. Nonetheless, critical challenges persist, including fragmented integration, interoperability gaps, workforce skill deficits, high implementation costs, and inadequate sustainability metrics. Conversely, notable opportunities emerge from technological innovation, cross-sector collaboration, and circular value creation.

Drawing on these insights, the study proposes a strategic GIS framework structured around four pillars: Technological Enablement, Sustainable Operations and Circularity, Human-Centric Integration, and Governance and Policy Alignment. The framework is implemented through a five-phase roadmap—Assessment, Design, Deployment, Optimization, and Sustainability & Resilience—demonstrating how Industry 4.0/5.0 technologies can strengthen operational excellence methodologies such as Green Lean Six Sigma (GLSS). By integrating digital transformation, sustainability, and human-centric principles, the framework offers a practical pathway toward resilient, low-impact, and future-ready industrial ecosystems that foster efficiency, environmental stewardship, and long-term socio-economic value creation.

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Abbreviations

Abbreviation	Full Term	Definition
AI	Artificial Intelligence	Systems performing tasks requiring human intelligence, including analytics.
AIM	Asset Integrity Management	Ensures safe, efficient, and reliable asset performance.
AIoT	Artificial Intelligence of Things	AI is integrated into IoT devices for automation and predictive maintenance.
AR	Augmented Reality	Overlays digital info onto the physical environment for visualization or training.
BIM	Building Information Modeling	Digital representation of infrastructure for design and operation.
CEPs	Circular Economic Practices	Resource-efficient, reuse, and closed-loop production strategies.
CPS	Cyber-Physical Systems	Combines computational algorithms with physical processes for real-time control.
DMAIC	Define, Measure, Analyze, Improve, Control	Lean Six Sigma methodology for structured process improvement.
DT	Digital Twin	Virtual model of physical assets for simulation and monitoring.
ERP	Enterprise Resource Planning	Software managing core business processes and resources.
ESG	Environmental, Social, and Governance	Criteria for sustainability and ethical impact in decisions.

GIIoT	Green Industrial IoT	IoT applications enhancing industrial sustainability.
GIS	Green Industrial Systems	Systems optimized for efficiency, low environmental impact, and socio-economic value.
GLS	Green Lean Six Sigma	Framework combining Lean Six Sigma, sustainability, digital, and human-centric innovation.
IoT	Internet of Things	Network of devices enabling real-time data collection and communication.
KPI	Key Performance Indicator	Quantifiable metric to evaluate operational, environmental, or social performance.
LSS	Lean Six Sigma	Combines Lean (waste reduction) and Six Sigma (defect reduction) for quality improvement.
MES	Manufacturing Execution System	Platforms for real-time monitoring and control of manufacturing operations.
ML	Machine Learning	AI subset where systems learn from data to improve performance.
OEE	Overall Equipment Effectiveness	Metric evaluating equipment productivity considering availability, performance, and quality.
R&D	Research and Development	Activities for innovation, design, and process improvement.
RAMS	Reliability, Availability, Maintainability, Safety	Measures evaluating system performance, reliability, and safety.
RCM	Reliability-Centered Maintenance	Maintenance strategy ensuring reliability while minimizing risk.
SLR	Systematic Literature Review	Structured review summarizing and synthesizing evidence.
SMEs	Small and Medium-sized Enterprises	Organizations of limited scale, often driving innovation.
TPM	Total Productive Maintenance	Maintenance approach emphasizing proactive and preventive strategies.
VR	Virtual Reality	Immersive digital environments for simulation, training, and visualization.

Introduction

Sustainability has emerged as a strategic imperative for industrial organizations, driven by environmental challenges, resource limitations, and increasingly stringent regulations [1,2]. Modern manufacturing operations are expected to minimize environmental impacts while maintaining competitiveness, efficiency, and innovation. In this context, Green Industrial Systems (GIS) have gained prominence as an integrative framework that combines sustainable practices, advanced digital technologies, and strategic management to enhance environmental, economic, and social performance [3,4]. GIS represents a transformative approach, aligning sustainable manufacturing, circular economy principles, and enabling technologies to deliver resilient, resource-efficient, and future-ready industrial operations.

Sustainable manufacturing plays a central role in aligning industrial operations with environmental responsibility. It promotes cleaner production, optimized energy and resource use, and waste minimization across the product lifecycle, reducing pollution and conserving resources while improving long-term operational performance [5]. Complementary practices—including eco-design, recycling, resource recovery, and circular product management—further reduce ecological footprints and enhance efficiency, resilience, and competitiveness [6].

Green manufacturing focuses on minimizing environmental impact through efficient use of materials, energy, and natural resources, while reducing toxic emissions, waste, and carbon footprints [7]. Facilities increasingly adopt eco-efficient technologies, renewable energy solutions, and closed-loop production systems, aligning operations with global sustainability goals and corporate social responsibility initiatives.

Beyond environmental benefits, green manufacturing provides economic advantages, including cost reduction, improved operational efficiency, and enhanced competitiveness [8]. When combined with Lean and Six Sigma methodologies, firms can systematically reduce process inefficiencies, optimize resource consumption, and minimize operational waste. Frameworks such as Green Lean Six Sigma (GLSS) exemplify this integration, enabling organizations to achieve measurable gains in energy efficiency, waste reduction, and overall productivity [9].

Lean and Green methodologies are closely interconnected: Lean emphasizes process efficiency and waste elimination, while Green extends these principles across the entire product lifecycle [10]. Six Sigma complements both by offering a data-driven, structured methodology to measure, analyze, and control process and energy variability, supporting evidence-based decision-making [11]. The integration of Lean, Green, and Six Sigma forms the GLSS framework, a holistic approach addressing operational waste and resource consumption while enhancing the triple bottom line: economic, environmental, and social performance.

The transition from Industry 4.0 to Industry 5.0 further strengthens GIS. Industry 4.0 technologies—including AI, IoT, blockchain, digital twins, and additive manufacturing—enable intelligent, energy-efficient, and low-impact production systems [12,13]. Industry 5.0 builds on this foundation by emphasizing human-centric, ethical, and collaborative innovation, ensuring technological advancement delivers societal value, workforce well-being, and operational resilience [14,15]. By integrating eco-efficient practices with enabling technologies, GIS not only reduces environmental impact and optimizes resource use but also fosters innovation, human-centric value creation, and organizational agility, positioning it as a cornerstone of future-ready industrial ecosystems.

Despite increasing research on sustainable manufacturing, circular economy practices, and digital technologies, the literature remains fragmented, and a unified GIS framework is still lacking [2,16]. In particular, the potential of Industry 5.0 technologies to reinforce operational excellence methodologies, such as GLSS, remains underexplored in resource-intensive and sustainability-driven contexts [17,18]. Addressing this gap is critical for organizations seeking to simultaneously optimize operational performance, sustainability, and human-centric value [19,20].

To address these gaps, this study conducts a systematic literature review (SLR) of publications from 2015–2025, focusing on sustainable manufacturing, circular economy practices, AI-driven technologies, smart factories, green production, and sustainable materials. The review identifies key trends, technological enablers, implementation challenges, and strategic opportunities. Based on these insights, a strategic GIS framework is proposed, integrating Industry 4.0/5.0 technologies, sustainable manufacturing, and circular economy principles, while demonstrating how Industry 5.0 can enhance operational excellence to achieve resilient, low-impact, and future-ready industrial systems.

The paper is organized as follows: Section 2 reviews sustainable manufacturing and circular economy practices; Section 3 analyzes key challenges and opportunities; Section 4 presents a strategic GIS framework; Section 5 outlines a Green Lean Six Sigma framework; and Section 6 concludes with insights and recommendations for future research.

Literature Review on Green Industrial Systems (GIS)

Green Industrial Systems (GIS) integrate sustainable practices, advanced digital technologies, and strategic management to enhance environmental performance, resource efficiency, and socio-economic resilience [3,4]. GIS aligns industrial operations with sustainability goals, circular economy principles, and digital transformation, enabling long-term competitiveness while minimizing environmental impact. Despite extensive research on clean production, circular economy models, and Industry 4.0/5.0 technologies, few studies synthesize these dimensions into a unified GIS framework. Current literature often remains fragmented, lacks integration of technological and strategic enablers, and provides limited empirical evidence across industrial sectors [2,16].

A systematic literature review (SLR) of publications from 2015–2025, retrieved from Scopus, Web of Science, and ScienceDirect, employed keywords such as “green industry,” “sustainable manufacturing,” “circular economy,” and “Industry 4.0/5.0.” Only English-language journal and conference papers were included, following a multi-stage protocol encompassing problem formulation, eligibility assessment, data extraction, and thematic synthesis [21].

Sustainable Manufacturing and Circular Economy

Sustainable manufacturing integrates digital technologies with environmentally responsible production to reduce ecological footprints while enhancing resource efficiency, process performance, and cost-effectiveness [22,23]. Industry 5.0 advances sustainability from compliance to strategic value creation, applying human-centric, intelligent, and eco-efficient innovations to reduce emissions, waste, and energy use while strengthening resilience and competitiveness [14].

Operationally, GIS combines lean production methods—such as value stream mapping, process optimization, and just-in-time systems—with circular practices, including recycling, remanufacturing, and by-product valorization [4,23,24]. Energy- and water-saving interventions, including heat recovery systems, variable-speed drives, renewable energy integration, and AI-assisted optimization, further enhance efficiency [12]. Circular product design strategies—modularity, disassembly, repairability, and recyclability—extend product lifetimes and reduce reliance on virgin materials [2].

Sustainable materials—including biodegradable polymers, bio-based composites, and eco-functional materials—enhance circularity and reduce carbon footprints [25,26,27]. Advanced materials, such as self-healing polymers and nanocellulose composites, combine sustainability with adaptive functionality (Klemm et al., 2011). Circular strategies—including reduce, reuse, recycle, and remanufacture—are implemented through Design for Circularity (DfC) and industrial symbiosis [1,4,28].

Real-world applications confirm GIS benefits. Batouta report that a Moroccan plastic recycling plant achieved a 22% reduction in energy consumption, $96,884 in annual savings, and 332 tons of CO_2 emissions avoided, with a payback period under one year [29].

Digital Technologies and Smart Manufacturing

Digital technologies underpin GIS, enabling intelligent, energy-efficient, and low-impact operations [3]. AI and Machine Learning optimize energy management, minimize waste, and enable predictive analytics for load forecasting, real-time scheduling, and lifecycle decision-making [12]. Integration with MES, ERP, and digital twins allows real-time adjustments, scenario simulations, and workflow optimization [13].

Smart factories exemplify the convergence of cyber-physical systems (CPS), IoT, AI, and ML, creating autonomous, interconnected, and self-optimizing production environments [30]. High-speed networks (5G) support machine coordination, while digital twins provide predictive insights on energy use, performance, and environmental impact. AI-driven dashboards and AR/VR interfaces enhance human-centric operations and collaborative decision-making [15].

Organizational Integration and Dynamic Capabilities

Effective GIS implementation requires alignment of technological, operational, and organizational capabilities. Xu show that integrating Green Industrial IoT (GIIoT), circular economic practices (CEPs), and dynamic capabilities (DC) enhances environmental performance, with DC mediating technology adoption and CEPs partially mediating sustainability outcomes [20].

Industry 5.0 emphasizes human-centric collaboration, ethical engineering, and social inclusivity [15]. Boumsisse integrate Industry 5.0 technologies into the Green Lean Six Sigma (GLSS) DMAIC cycle, improving sustainability and operational efficiency [17]. Innovations—including AI-assisted materials discovery, bio-inspired design, renewable energy integration, and autonomous logistics—support self-sustaining, low-impact industrial ecosystems [19].

Policy and governance are crucial for supporting GIS adoption. Xu shows that China’s Made in China 2025 initiative enhanced green innovation through tax incentives, environmental subsidies, and corporate social responsibility programs [31]. Allan and Nahm highlight differences between interventionist and market-driven policies, showing that policy effectiveness depends on industry uncertainty, domestic industry position, and supply chain maturity [32]. Wang demonstrate that green technological innovation drives industrial structural optimization under carbon constraints, supporting sustainable economic transformation with regional heterogeneity [33].

Green Lean Six Sigma and Operational Excellence

Lean Six Sigma (LSS) is a management methodology that systematically eliminates waste and defects by addressing root causes. It integrates Lean principles, focusing on process efficiency and flow, with Six Sigma techniques, emphasizing data-driven quality control and variability reduction. Originating from the Toyota Production System, Lean has been widely adopted across industries, offering a structured framework for operational optimization and continuous improvement. Empirical studies show that Lean contributes significantly to sustainable manufacturing, delivering environmental and economic benefits while enhancing process innovation and organizational performance [34-38].

LSS is implemented through the Define-Measure-Analyze-Improve-Control (DMAIC) cycle, using tools such as Pareto charts, Statistical Process Control (SPC), the Five Whys, and Failure Modes and Effects Analysis (FMEA). These tools help identify inefficiencies, reduce variability, and eliminate non-value-added activities. Growing environmental concerns have led organizations to integrate sustainability into LSS, giving rise to Green Lean Six Sigma (GLSS), which aligns operational excellence with environmental objectives, delivering measurable improvements in energy efficiency, waste reduction, and resource optimization [39].

The combination of Green, Lean, and Six Sigma methodologies provides a comprehensive approach to operational excellence, sustainability, and continuous improvement [18,40,41]. Frameworks such as Big Data Analytics–GLSS (BDA-GLSS) embed predictive analytics, real-time quality control, and proactive maintenance, enhancing technological readiness, decision-making, and sustainability performance [18]. Similarly, DMAIC-based GLSS frameworks integrate essential enablers, analytical tools, and performance indicators, providing a structured pathway for implementing sustainable practices [41].

Recent research emphasizes the synergy between Industry 5.0 technologies and GLSS. Integrating Lean principles with AI, collaborative robotics (cobots), and digital tools enhances operational performance, innovation, and sustainability, supporting the evolution toward Lean 5.0 [34,42,43]. Industry 4.0/5.0 technologies enable resource optimization, energy reduction, and superior quality, while Industry 5.0 adds human-centric, ethical, and collaborative dimensions, ensuring that technological innovation delivers societal value and workforce well-being [14,15,44].

GLSS integrates sustainability into manufacturing by combining Lean efficiency, Six Sigma rigor, and environmental considerations, resulting in high productivity, optimized resource utilization, minimized waste, and reduced environmental impact [45-47]. Eco-conscious practices, such as energy efficiency, recycling, and resource recovery, enable firms to remain competitive while minimizing ecological footprints. Practical applications demonstrate GLSS effectiveness, including reduced delivery times and improved resource utilization in healthcare and manufacturing sectors [48]. GLSS also forms the basis of sustainable environmental management systems, aligning operational excellence with environmental goals [49].

Rahardjo present a case study in the plywood industry illustrating the integration of GLSS with the Theory of Inventive Problem Solving (TRIZ) [50]. This combination enables structured innovation and problem-solving, increasing industrial waste recycling rates from 92–93% to over 95%. The study highlights that integrating TRIZ with GLSS forms a comprehensive, innovation-oriented framework capable of addressing complex sustainability challenges.

Combining GLSS with Industry 4.0/5.0 tools, including IoT, AI, digital twins, predictive analytics, and automation, enables real-time monitoring, predictive maintenance, and data-driven decision-making, enhancing efficiency and sustainability outcomes. Industry 5.0 emphasizes human-centric and ethical innovation, ensuring technological advances deliver societal value, workforce well-being, and organizational resilience. Monitoring productivity and environmental indicators ensures that operational efficiency, resource optimization, and ecological responsibility are mutually reinforced [45].

Despite significant progress, the systematic integration of Industry 5.0 technologies within GLSS remains underexplored, particularly in complex, resource-intensive, and sustainability-driven environments. Addressing this gap is essential to realizing data-driven, human-centered, and sustainable industrial systems, advancing operational excellence, innovation, and resilient industrial transformation.

Green Industrial Systems (GIS) represent the convergence of technological, operational, and strategic dimensions for sustainable industrial transformation. Industry 4.0/5.0 technologies provide the digital foundation, while circular economy principles, human-centric approaches, and supportive policies enable effective implementation. Integrated, these components generate significant environmental, economic, and social benefits. Key challenges include interoperability, workforce upskilling, implementation costs, and standardization of sustainability metrics. This review establishes a foundation for a unified GIS framework and structured implementation roadmap, guiding organizations toward resilient, low-impact, and future-ready industrial systems.

Challenges and Research Gaps in Green Industrial Systems

Despite significant progress, GIS adoption faces technological, organizational, operational, and policy-related challenges. Table 1 provides a structured overview of these challenges, research gaps, and potential solutions. Addressing these barriers requires coordinated integration of advanced digital technologies, human-centric practices, sustainable materials, and strategic management to foster resilient, circular, and future-ready industrial ecosystems.

Technological challenges include interoperability, cybersecurity, energy efficiency, and scalability issues in AI, IoT, blockchain, and CPS, which impede seamless industrial integration [21,51,52]. Fragmented or inconsistent data restricts real-time decision-making and predictive analytics. LCA is hindered by incomplete data, methodological inconsistencies, and limited expertise [26,53]. Mitigation strategies include interoperable, energy-efficient infrastructures, standardized protocols, AI-assisted LCA tools, and change management programs emphasizing economic, environmental, and social benefits.

Human-centric and organizational factors are equally critical. Fragmented research and limited integration of sustainability, circularity, and Industry 4.0/5.0 technologies restrict holistic GIS frameworks [1,28,54]. Workforce challenges—including skill gaps, insufficient training, and low organizational readiness—further hinder adoption [15,21,51,52]. Addressing these barriers requires integrated frameworks linking technological, operational, and managerial dimensions, hybrid workforce development programs, and participatory management supported by stakeholder engagement.

Material, process, and operational constraints include high implementation costs, limited scalability of sustainable materials and circular processes, and supply chain complexity [2,25,26,27,55,56]. Effective strategies include phased technology adoption, scalable materials investment, optimized circular processes, IoT- and blockchain-enabled supply chains, and decentralized, adaptive production systems supported by predictive analytics and scenario planning.

Policy, market, and evidence-related challenges further impede adoption. Regulatory inconsistencies, fragmented policies, and market disparities—particularly affecting SMEs—limit uptake [2,30]. Overlapping environmental standards, certifications, and reporting requirements increase compliance burdens. The lack of harmonized sustainability metrics, standardized KPIs, and circularity indicators restricts benchmarking, cross-sector comparison, and GIS evaluation [26,53,55,57]. Limited collaboration among industry, academia, and government further hampers knowledge sharing and coordinated action [2,30]. Most studies rely on secondary data, pilot projects, or sector-specific analyses, limiting generalizability [1,2,4,15,28,30,54]. Addressing these gaps requires regulatory harmonization, targeted incentives, cross-sector collaboration, standardized sustainability metrics, and longitudinal, multi-sector studies tracking KPIs, digital adoption, and operational outcomes.

In conclusion, overcoming technological, human-centric, operational, and policy-related challenges is essential to enable resilient, circular, and human-centered industrial ecosystems. Integrating digital technologies, workforce development, sustainable materials, and evidence-based management frameworks will accelerate the transition toward sustainable, future-ready, and environmentally responsible manufacturing systems.

Table 1: Challenges, Research Gaps, and Recommendations in Green Industrial Systems (GIS)

Group	Challenge	Research Gaps	Recommendations
Technological	Digitalization Limitations	AI, IoT, blockchain, CPS face interoperability, cybersecurity, energy, and scalability issues [21,51,52].	Develop secure, energy-efficient, interoperable infrastructures; adopt standardized, modular, scalable solutions.
	Data Management	Fragmented or insecure data limits real-time decision-making [51,52].	Standardize data protocols; implement integrated cloud platforms; enhance cybersecurity; train workforce in analytics.
	Lifecycle Assessment	Incomplete data and inconsistent methods hinder comprehensive LCA [26,53].	Develop standardized, AI-assisted LCA tools; provide practitioner training.
	Technology Adoption Resistance	Organizational inertia and cultural barriers slow adoption [15,30].	Apply change management, leadership engagement, and awareness campaigns; highlight economic, environmental, and social benefits.
Human-Centric / Organizational	Fragmentation & Integration	Sustainability, circularity, and Industry 4.0/5.0 often studied separately [1,28,54].	Develop integrated GIS frameworks; promote cross-disciplinary research.
	Workforce Challenges	Skill gaps, limited training, and low readiness hinder Industry 5.0 adoption [15,21,51,52].	Implement hybrid skill programs in AI, robotics, and sustainability; foster participatory management and supportive culture.
Material, Process & Operational	High Implementation Costs	Initial investments for sustainable technologies and circular processes are often prohibitive, especially for SMEs [2,25].	Provide financial incentives, subsidies, and phased/modular implementation strategies.
	Material & Process Scaling	Cost, performance, and industrial compatibility limit scaling of sustainable materials and circular processes [25,26,27,55,56].	Invest in scalable materials; optimize circular processes; implement predictive process control.
	Supply Chain Complexity	Limited visibility and traceability across multi-tier networks [2,16].	Deploy IoT, blockchain, cloud platforms; foster collaboration and transparency.
	Resilience to Disruptions	Limited research on adaptive systems for market, supply chain, and climate risks [19].	Design decentralized, adaptive systems; use predictive analytics, scenario planning, and risk management.
Policy, Market & Evidence	Policy & Market Barriers	Regulatory inconsistencies and market disparities, especially for SMEs [2,30].	Harmonize regulations; provide incentives; support SMEs; promote cross-sector collaboration.

	Regulatory Complexity	Overlapping environmental standards and certifications [2].	Harmonize standards; simplify compliance; provide clear industry guidance.
	Metrics & Standardization	Lack of harmonized KPIs and circularity indicators [26,53,55,57].	Establish standardized KPIs and LCA methods; integrate environmental, social, and economic metrics.
	Cross-Sector Collaboration	Limited collaboration between industry, academia, and government [2,30].	Promote public-private partnerships, joint research, and innovation networks.
	Empirical Evidence Gaps	Reliance on secondary data, pilot projects, or sector-specific studies limits generalizability [1,2,4,15,28,30,54].	Conduct longitudinal, multi-sector studies; track KPIs, digital adoption, and operational outcomes; examine interactions among digital, circular, and human-centric strategies.

Strategic Framework for GIS Implementation

The adoption of Green Industrial Systems (GIS) requires a holistic strategy that integrates sustainable practices, advanced digital technologies, circular economy principles, and human-centric approaches. The proposed framework provides a structured roadmap for organizations transitioning toward resilient, efficient, and future-ready industrial ecosystems. By combining technological innovation with sustainable operational models and robust governance, GIS enables long-term value creation while addressing environmental and socio-economic challenges. As summarized in Table 2 and illustrated in Figure 1, the framework is organized around four interdependent pillars: Technological Enablement, Sustainable Operations and Circularity, Human-Centric Integration, and Governance and Policy Alignment.

The first pillar, Technological Enablement, emphasizes the application of advanced digital technologies to enhance operational performance, resource efficiency, and intelligent decision-making. Artificial Intelligence (AI) and Machine Learning (ML) enable predictive maintenance, process optimization, and waste reduction. Internet of Things (IoT) solutions provide real-time monitoring, improve resource visibility, and allow adaptive operational control. Blockchain and traceability systems ensure secure and transparent tracking of products, materials, and circular practices. Additive manufacturing and advanced materials support resource-efficient production, rapid prototyping, and eco-friendly material integration. Collectively, these technologies form the foundation for data-driven, intelligent, and low-impact industrial operations.

The second pillar, Sustainable Operations and Circularity, embeds environmental responsibility across the product lifecycle. Circular manufacturing reduces waste and extends product lifecycles through closed-loop production strategies. Lean and eco-efficient processes eliminate non-value-adding activities while improving energy, water, and material efficiency. The use of sustainable materials and renewable energy reduces environmental impact and promotes low-carbon production. Life-Cycle Assessment (LCA) and carbon accounting provide quantitative insights that guide evidence-based decision-making and continuous improvement. Together, these practices enable operations that are both environmentally responsible and economically viable.

The third pillar, Human-Centric Integration, highlights the pivotal role of people in sustainable industrial transformation, consistent with Industry 5.0 principles. Workforce development programs enhance competencies in digital technologies, sustainability, and circular economy practices. Collaborative robotics (cobots) and AR/VR interfaces improve safety, ergonomics, productivity, and real-time decision-making, fostering effective human-technology collaboration. Participatory management and stakeholder engagement promote shared governance, cross-functional collaboration, and a culture of continuous improvement, ensuring GIS transformation is socially inclusive and supported by a skilled, future-ready workforce.

The fourth pillar, Governance and Policy Alignment, provides the strategic, regulatory, and institutional framework critical for GIS implementation. Sustainability KPIs and standardized metrics enable systematic performance monitoring, while regulatory compliance and incentive mechanisms ensure alignment with national and international sustainability standards. Cross-sector collaboration fosters innovation, knowledge sharing, and coordinated action among industry, academia, and government. Strategic planning and risk management support scenario-based planning, resilience-building, and mitigation of operational, market, and climate-related risks. Collectively, these mechanisms ensure strategic coherence, transparency, and long-term alignment with global sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs).

GIS implementation follows a structured, phased approach (Table 3) to ensure a smooth, systematic, and measurable transition. **Phase 1:** Assessment establishes the foundation by evaluating operational conditions, digital readiness, and sustainability performance. Organizations conduct audits, assess energy, material, and waste efficiency, and identify gaps in circularity and sustainability practices, producing a baseline understanding of performance and identifying improvement opportunities.

Phase 2: Design defines the technological, operational, and human-centric interventions required for GIS adoption. Organizations develop a comprehensive strategy, select appropriate digital technologies, design circular and lean processes, set KPIs and sustainability targets, and plan workforce development initiatives. This phase produces a detailed implementation roadmap aligned with strategic objectives.

Phase 3: Deployment translates the design into actionable initiatives. Organizations integrate AI, IoT, blockchain, and additive manufacturing technologies, launch pilot circular and eco-efficient processes, implement workforce training programs, and deploy monitoring systems. This phase validates operational components, collects initial performance data, and advances workforce readiness.

Phase 4: Optimization focuses on refining processes and scaling successful initiatives. Pilot results are analyzed, technologies and workflows are fine-tuned, human-digital collaboration is enhanced, and best practices are standardized. The outcome is optimized GIS operations with improved efficiency, resource utilization, and sustainability performance, ready for organization-wide adoption.

Phase 5: Sustainability and Resilience institutionalize GIS practices for long-term impact. This phase embeds a culture of continuous improvement, strengthens innovation capabilities, ensures regulatory compliance, monitors KPIs, and addresses emerging risks. Organizations achieve resilient and adaptive operations that continuously respond to environmental, technological, and market dynamics while remaining aligned with global sustainability frameworks.

In summary, this strategic GIS framework and phased roadmap provide organizations with a systematic, actionable, and measurable pathway for integrating digital technologies, circular operations, human-centric practices, and governance mechanisms. By harmonizing these elements, organizations can develop resilient, efficient, low-impact, and future-ready industrial systems that deliver lasting economic, environmental, and social value in the era of Industry 4.0 and 5.0.

Table 2: Strategic Pillars and Key Components of GIS Implementation

Pillar	Key Components	Objectives / Functions	Representative Tools
Technological Enablement	Artificial Intelligence (AI) & Machine Learning (ML)	Enable predictive maintenance, optimize energy and resource use, support process modeling and waste reduction	Digital twins, predictive analytics, optimization algorithms
	Internet of Things (IoT)	Provide real-time monitoring, enhance resource visibility, enable adaptive operational control	IoT sensors, smart meters, connected devices, monitoring platforms
	Blockchain & Traceability	Ensure secure, transparent tracking of products, materials, and circular practices	Blockchain platforms, supply chain traceability systems
	Additive Manufacturing & Advanced Materials	Support resource-efficient production, rapid prototyping, and eco-friendly material integration	3D printing, biodegradable composites, lightweight materials
Sustainable Operations & Circularity	Circular Manufacturing	Minimize waste, extend product lifecycles, and implement closed-loop production systems	Reduce–Reuse–Recycle–Remanufacture strategies, circular supply chains
	Lean & Eco-efficient Processes	Eliminate non-value-adding activities and improve energy, water, and material efficiency	Lean manufacturing, process mapping, energy optimization programs
	Sustainable Materials & Renewable Energy	Reduce environmental footprint and promote low-carbon production	Recyclable/biodegradable materials, solar and wind energy integration
	Life-Cycle Assessment (LCA) & Carbon Accounting	Quantify environmental impacts and guide decision-making for continuous improvement	LCA software, carbon calculators, sustainability reporting tools
Human-Centric Integration	Workforce Development	Build competencies in digital technologies, sustainability, and circular economy practices	Training programs, workshops, e-learning platforms
	Collaborative Robotics (Cobots) & AR/VR Interfaces	Enhance safety, ergonomics, productivity, and real-time decision-making	Cobots, AR/VR simulation tools, real-time operational interfaces
	Participatory Management & Stakeholder Engagement	Promote collaboration, shared governance, and continuous improvement	Cross-functional teams, engagement platforms, feedback mechanisms
Governance & Policy Alignment	Sustainability KPIs & Standardized Metrics	Measure and monitor environmental, social, and economic performance	ESG metrics, sustainability dashboards, scorecards
	Regulatory Compliance & Incentives	Ensure adherence to laws, standards, and sustainability frameworks	ISO 14001, EU Green Deal, national regulations
	Cross-Sector Collaboration	Foster innovation, knowledge sharing, and coordinated action	Industry–academia–government partnerships, collaborative networks
	Strategic Planning & Risk Management	Anticipate and mitigate operational, market, and climate-related risks	Scenario analysis, risk assessment frameworks, resilience strategies

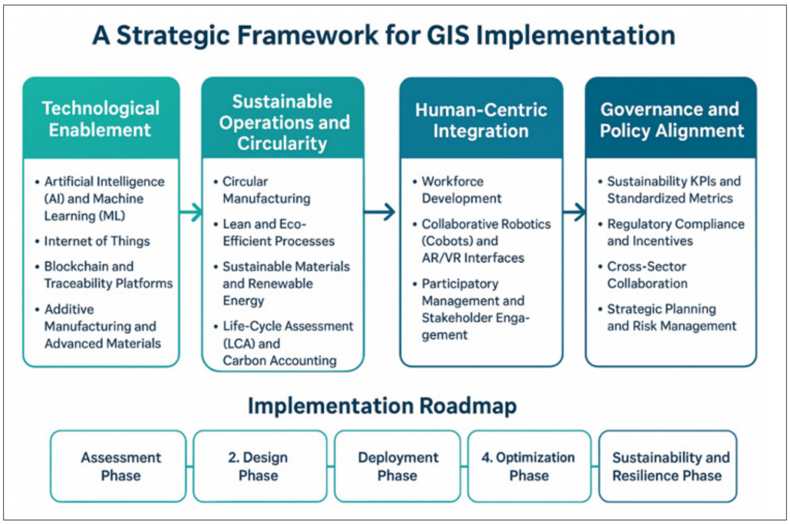

Figure 1: Strategic Framework for Implementing Green Industrial Systems (GIS)

Table 3: Implementation Roadmap for GIS

#	Phase	Objectives	Key Activities	Expected Outcomes
1	Assessment Phase	Evaluate current operations, digital readiness, and sustainability performance	Conduct operational audits; assess digital maturity; analyze energy, material, and waste efficiency; identify gaps in circularity and sustainability	Baseline performance assessment; identification of improvement opportunities; readiness evaluation for GIS adoption
2	Design Phase	Define technological, operational, and human-centric interventions	Develop GIS strategy; select digital technologies; design circular and lean processes; set KPIs and sustainability targets; plan workforce development	Comprehensive GIS implementation plan; clear performance targets; structured roadmap aligned with organizational goals
3	Deployment Phase	Implement GIS initiatives and pilot programs	Integrate AI, IoT, blockchain, and additive manufacturing; launch pilot circular and eco-efficient processes; conduct workforce training; deploy monitoring systems	Operational GIS components; validated pilot projects; initial performance data; progress in workforce capabilities
4	Optimization Phase	Refine processes, scale initiatives, and enhance efficiency	Analyze pilot results; fine-tune technologies and workflows; optimize human-digital collaboration; standardize best practices	Optimized GIS operations; improved efficiency and sustainability performance; scalable solutions ready for full implementation
5	Sustainability & Resilience Phase	Institutionalize GIS for long-term value, adaptability, and continuous improvement	Embed continuous improvement culture; strengthen innovation capabilities; maintain regulatory compliance; monitor KPIs; address emerging risks	Sustainable and resilient industrial operations; continuous performance monitoring; innovation-driven growth; alignment with SDGs and long-term strategic goals

Green Lean Six Sigma (GLS) Framework for Green Industrial Systems (GIS)

The Green Lean Six Sigma (GLS) framework offers a structured methodology for implementing Green Industrial Systems (GIS) by combining Lean Six Sigma principles with sustainability, advanced digital technologies, and human-centric innovation. GLS helps organizations improve operational efficiency, minimize waste, reduce environmental impact, and generate socio-economic value, fostering long-term resilience. By integrating eco-efficient practices across industrial processes and leveraging Industry 4.0/5.0 technologies, GLS supports triple-bottom-line performance, aligning economic, environmental, and social objectives.

Building on the traditional DMAIC (Define, Measure, Analyze, Improve, Control) cycle, GLS extends the methodology to incorporate sustainability, circularity, and human-centric considerations, providing a roadmap for low-impact, resilient, and future-ready industrial systems (see Table 4 and Figure 2):

- **Define Phase:** Set strategic environmental, operational, and social objectives; identify critical processes and stakeholders; and define measurable targets for energy efficiency, emission reduction, and circular material flows. Align initiatives with organizational strategy, stakeholder priorities, and regulatory requirements.
- **Measure Phase:** Quantify KPIs such as energy and water consumption, carbon footprint, and waste generation. Utilize IoT, digital twins, AI analytics, and predictive monitoring for real-time data collection and informed decision-making.
- **Analyze Phase:** Apply statistical analysis, predictive modeling, and AI-enabled simulations to identify process inefficiencies, environmental hotspots, and operational risks. Scenario modeling evaluates interventions and forecasts outcomes, linking process optimization with sustainability assessment.
- **Improve Phase:** Streamline workflows using Lean methods and reduce defects with Six Sigma. Introduce green interventions—including cleaner production, modular design, circular material flows, energy-efficient technologies, and resource recovery. Industry 5.0 principles foster human-centric collaboration, workforce engagement, and co-created

sustainable solutions.

- **Control Phase:** Sustain improvements through continuous monitoring, AI-enabled dashboards, automated alerts, and feedback loops. Ensure compliance with environmental standards and circularity objectives while reinforcing adaptability and long-term resilience.

The GLS framework enables a synergistic integration of operational excellence, sustainability, and digital-human innovation, connecting technological advancement, circular practices, and human-centric approaches with organizational goals.

Key Benefits of GLS for GIS

- **Operational Excellence:** Streamlined processes, defect reduction, and improved productivity.
- **Environmental Sustainability:** Reduced emissions, circularity integration, and eco-efficient lifecycle management.
- **Human-Centric Innovation:** Workforce engagement, collaborative problem-solving, and green skill development.
- **Data-Driven Decision Making:** Real-time monitoring, predictive analytics, and AI-enabled insights.
- **Resilience and Adaptability:** Continuous improvement and agile response to change.

GLS operationalizes GIS by combining Lean efficiency, Six Sigma quality, sustainability principles, and digital-human innovation, providing a scalable, measurable, and strategic methodology for developing low-impact, resource-efficient, and future-ready industrial systems that deliver long-term economic, environmental, and social value.

Strategic Objectives and KPIs of GLSS

GLSS focuses on integrating operational excellence, environmental sustainability, circularity, and human-centric innovation to ensure GIS achieve measurable improvements in efficiency, resource utilization, and socio-environmental value. Each objective is linked to KPIs, enabling data-driven monitoring, continuous improvement, and strategic decision-making. Table 5 summarizes the strategic objectives, KPIs, digital enablers, and strategic impact of GLSS implementation. The framework provides a structured roadmap for resilient, low-impact, and future-ready industrial systems, with each objective supported by advanced digital technologies:

- **Operational Excellence:** Streamline processes, reduce variability, and increase productivity. KPIs include cycle time reduction, defect rates, Overall Equipment Effectiveness (OEE), production throughput, and value-added ratio. ERP, MES, AI-driven optimization, automation, and predictive analytics enable real-time improvements.
- **Environmental Sustainability:** Minimize industrial footprints and implement eco-efficient practices. KPIs include energy and water consumption, carbon footprint, waste reduction, recycling/reuse rates, and ISO 14001/ EMAS compliance. IoT sensors, digital twins, AI-enabled monitoring, and sustainability dashboards provide real-time insights.
- **Resource Efficiency and Circularity:** Optimize resource use and integrate circular material flows. KPIs include material utilization efficiency, proportion of recycled/reused materials, lifecycle assessment (LCA) scores, and reduced non-renewable resource consumption. AI/ML optimization, digital twin simulations, blockchain traceability, and IoT monitoring support sustainable production systems.
- **Human-Centric Innovation:** Promote workforce engagement, collaboration, and co-created solutions. KPIs include employee participation, green skills training, improvement projects, safety incidents, and human-machine collaboration metrics. AR/VR training, collaborative platforms, AI-assisted decision support, and human-digital interfaces enhance engagement and innovation.
- **Data-Driven Decision Making:** Enable predictive, real-time, and evidence-based operations. KPIs include data accuracy, predictive maintenance actions, analytics insights implemented, and unplanned downtime reduction. IoT networks, AI/ML analytics, digital twins, predictive maintenance platforms, and cloud dashboards provide actionable insights.
- **Resilience and Adaptability:** Ensure robust, agile, and sustainable operations. KPIs include response time to disruptions, recovery rates, continuous improvement cycles, and year-on-year improvements in energy, emissions, and waste. AI/ML scenario modeling, digital twins, automated alerts, and real-time monitoring enable proactive responses.

In summary, Table 5 provides a holistic roadmap for GLSS implementation in GIS, connecting measurable KPIs, digital enablers, and strategic outcomes. By integrating operational efficiency, sustainability, circularity, human-centric innovation, data-driven insights, and resilience, organizations can achieve long-term value while transitioning toward low-impact, future-ready industrial systems.

Table 4: Green Lean Six Sigma (GLS) Framework for Green Industrial Systems (GIS)

DMAIC Phase	Objectives	Key Activities	Industry 4.0/5.0 Enablers	Sustainability & Circularity Focus	Human-Centric & Strategic Integration
Define	Set strategic sustainability and operational goals	Identify critical processes, stakeholders, and KPIs	ERP, MES, digital dashboards	Energy efficiency, emission reduction, circular material flows	Align initiatives with strategy, regulations, and stakeholder priorities
Measure	Quantify baseline performance	Collect data on energy, materials, emissions, and waste	IoT sensors, digital twins, AI analytics	Resource use, waste generation, carbon footprint	Enable informed decision-making and workforce engagement
Analyze	Identify inefficiencies and improvement opportunities	Root cause analysis, process simulation, scenario modeling	AI/ML, process mining, predictive analytics	Detect environmental hotspots and material inefficiencies	Support human-machine collaboration and co-created solutions
Improve	Implement process and sustainability enhancements	Lean process redesign, Six Sigma defect reduction, circular practices	AI-driven optimization, automation, AR/VR guidance	Cleaner production, modular design, recycling, resource recovery	Foster workforce engagement, innovation, and human-centric solutions

Control	Sustain improvements and continuous optimization	Monitoring, feedback loops, compliance tracking	Real-time dashboards, predictive maintenance, automated alerts	Maintain circularity, eco-efficient operations, and energy efficiency	Promote continuous learning, resilience, and adaptability

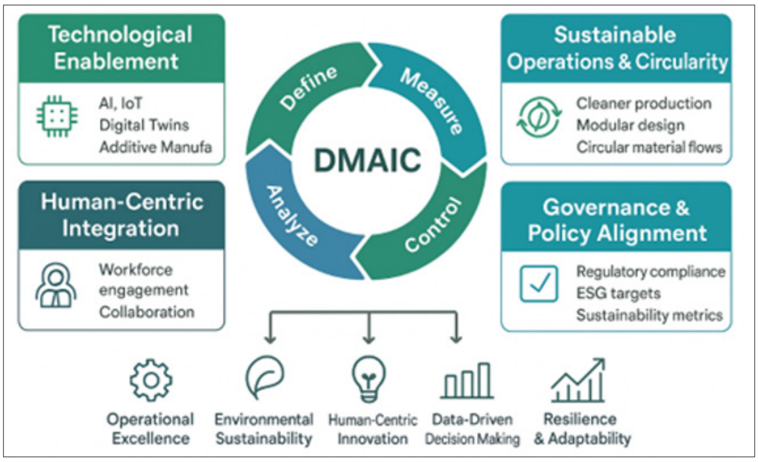

Figure 2: Green Lean Six Sigma (GLSS) Framework for Green Industrial Systems (GIS)

Table 5: Strategic Objectives and KPIs for GLSS in GIS

#	Strategic Objective	Key Performance Indicators (KPIs)	Digital Enablers	Strategic Impact
1	Operational Excellence – Streamline processes and boost productivity	Cycle time reduction (%), defect rate/PPM, OEE, throughput, value-added ratio	ERP, MES, AI optimization, automation, predictive analytics	Optimized workflows, higher productivity, reduced waste, agile operations
2	Environmental Sustainability – Minimize environmental footprint	Energy & water use per unit, carbon footprint, waste reduction (%), recycling rate (%), ISO 14001/EMAS compliance	IoT sensors, digital twins, AI monitoring, sustainability dashboards	Lower carbon/resource footprint, regulatory compliance, eco-efficient operations
3	Resource Efficiency & Circularity – Optimize resources and circular material flows	Material utilization (%), recycled/reused proportion (%), LCA scores, non-renewable resource reduction (%)	AI/ML optimization, digital twins, blockchain traceability, IoT monitoring	Reduced raw material dependency, cost savings, circular production systems
4	Human-Centric Innovation – Enhance workforce engagement and collaboration	Employee participation (%), green skills training, co-created improvement projects, safety incidents, human-machine collaboration	AR/VR training, collaborative platforms, AI-assisted decision support, human-digital interfaces	Engaged workforce, innovation culture, safer operations, human-digital synergy
5	Data-Driven Decision Making – Enable predictive, evidence-based operations	Data accuracy (%), predictive maintenance triggered (%), insights implemented (%), unplanned downtime reduction (%)	IoT networks, AI/ML analytics, digital twins, cloud dashboards	Faster, evidence-based decisions, improved transparency, higher reliability
6	Resilience & Adaptability – Ensure robust, agile, and sustainable operations	Response time, recovery rate (%), continuous improvement cycles, year-on-year energy/emissions/waste improvement	AI/ML scenario modeling, digital twins, automated alerts, real-time monitoring	Increased operational and environmental resilience, agile adaptation, sustainable performance

Conclusion and Future Work

This study examined Green Industrial Systems (GIS) as an integrative framework that combines sustainable practices, advanced digital technologies, and strategic management to enhance environmental performance, resource efficiency, and socio-economic resilience. GIS provides a holistic pathway for transforming industrial operations into low-impact, resource-efficient, and socially responsible systems, aligning productivity with long-term sustainability and competitiveness.

The systematic literature review (2015–2025) revealed that Industry 4.0 technologies—including AI, IoT, blockchain, digital twins, and additive manufacturing—enable energy efficiency, predictive maintenance, waste reduction, and circular operations, while Industry 5.0 principles enhance human-centricity, ethical engineering, collaboration, and societal value creation. Key adoption challenges include fragmented integration, interoperability gaps, workforce skill deficits, high implementation costs, and limited sustainability metrics, whereas opportunities emerge from technological innovation, cross-sector collaboration, and circular value creation.

Based on these insights, a strategic GIS framework was proposed, structured around four pillars—Technological Enablement, Sustainable Operations and Circularity, Human-Centric Integration, and Governance & Policy Alignment—and supported by a five-phase roadmap: Assessment, Design, Deployment, Optimization, and Sustainability & Resilience. The framework demonstrates how Industry 5.0 technologies can reinforce operational excellence methodologies, such as Green Lean Six Sigma (GLSS), enabling organizations to optimize processes, improve sustainability outcomes, and build resilient, future-ready industrial systems [58-62].

Theoretical Implications: The framework advances understanding of the integration of Industry 4.0/5.0 technologies, circular economy principles, and human-centric approaches, providing a foundation for research on sustainable industrial innovation and organizational resilience.

Practical Implications: It offers a clear roadmap for implementing advanced technologies, circular operations, and workforce development, enhancing operational efficiency, resource optimization, and sustainable value creation.

Managerial Implications: Managers can prioritize technology investments, adopt eco-efficient practices, strengthen governance structures, and align operations with sustainability objectives.

Limitations and Future Research: Derived from a literature review, the framework requires empirical validation to confirm its applicability across industries, organizational maturity levels, and regulatory contexts. Future research should explore the integration of emerging Industry 6.0 technologies (e.g., emotional AI, human-digital twins, regenerative systems), develop standardized metrics and monitoring tools, address adoption barriers, and foster cross-sector collaboration to further strengthen GIS adoption and impact, enabling resilient, low-impact, and socially responsible industrial ecosystems.

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