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Sustainability in industry 4.0 and 5.0: Environmental, Social, and Governance (ESG)-driven practices

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Abstract

Industry 5.0 and the integration of the digital transformation with sustainability imperatives brings these two worlds closer together and creates a unique dilemma for the modern industry which comes under pressure from both sides. Classic Environmental, Social and Governance (ESG) investing is not equipped to deal with the complex, interrelated problems of climate change, social inequality and corporate accountability that come hand-in-hand with a digital economy that few understand or can square off. This review of literature studies how ESG implementation, reporting and performance measurement are being redefined across industries due to the advent of emerging technologies such as artificial intelligence, machine learning, blockchain and internet-of-things. The systematic PRISMA approach was used by analyzing a pool of 97 studies. The research shows significant progress in predictive analytics for environmental impact assessment, AI-driven sustainability reporting and blockchain-based supply-chain transparency, as well as the application of machine-learning techniques to ESG risk. The results indicate that smart technology, predictive analytics, and responsible use of technology are key enablers in sustainable supply chain management and renewable energy implementation as well as overall sustainability reporting. This study contributes to the theoretical development and practical application of ESG-driven strategies in digitally empowered industrial environments and provides a deeper understanding of governance models, investment patterns, and performance-testing methods promoting economic prosperity while preserving the environment and ensuring social responsibility, thereby progressing the global sustainability agenda in an increasingly inter-dependent yet technology-enabled era.

Keywords: Artificial intelligence, Sustainable development, Sustainability, ESG, Investments, Machine learning.

1. Introduction

The current industrial landscape represents a tipping point where the technology revolution meets pressing sustainability challenges. The fourth Industrial Revolution, Industry 4.0, is a new era that has completely revolutionized the way manufacturing and services sectors work by combining cyber physical systems, IoT, Cloud computing, cognitive system [1]. Towards Industry of Things and Habitats Since the world today is moving towards deeper stages of the fourth industrial revolution, industry should transition to an era where humans are at the center and sustainability and society accompany technological progress. While entering these sustainable-based approaches in Industry 5.0, organizations have increasing societal demands due to accumulation pressures to adopt operations according to ESG compliance related with global challenges such as climate change, resource scarcity, social inequality and ethical issues that works on targeting these problems [1,2]. It was in this context that Industry 4.0 became a game changer and smart factory as well as autonomous systems became feasible, taking advantage of decision making based on data. This revolution led to enormous efficiency, productivity and operational optimization in different sectors [3-5]. However, the early ramp-up of technology solutions sometimes tended to take precedence over key sustainable factors and have unfortunately resulted in accelerating energy use but also generating electronic waste and possibly contributing to social disruption via job losses. The insight that technological advancement needs to go hand in hand with respect for the environment and social justice was a driving force behind the transformation towards Industry 5.0, which does not only focus on technological innovation but explicitly includes sustainability and human-centric approaches as matters of paradigmatic change.

Environmental, Social and Governance frameworks have grown from being niche corporate social responsibility programmes to mainstream business drivers which impact on decisions regarding investment, regulation compliance, stakeholder expectations and competitive position [6,7]. Environmental aspects include mitigation of climate change, reduction of carbon footprint, principles of circular economy, resource efficiency, biodiversity protection and prevention of pollution [2,8-10]. Social factors include labour practices, human rights, diversity and inclusion, community involvement, health and safety within the workplace as well as equitable value distribution [1,11-12]. The governance aspects include ethical leadership, transparency and accountability, risk management, anti-corruption initiatives and stakeholder inclusiveness in decision making. This paper summarizes the latest progress on ESG-driven operations with regard to artificial intelligence, big data, IoT, blockchain, fintech, and decision sciences. We map applications per sector, analyze methods and tools, compare frameworks and highlight challenges and opportunities [13-15]. The work contributes to three existing gaps in literature, the low link between Industry 4.0 technologies and the human-centred focus of Industry 5.0, the lack of an end-to-end, machine-readable ESG data pipeline from sensor to investor and not enough attentiveness on model governance, equity, and explainability in sustainability analytics. The aims and objectives are to infuse innovative emergent techniques of high translational potential, to introduce a cohered governance and architecture view, and set out future research where credible real-time ESG performance may be actualized. The deliverable is an integrated framework that puts together operational data, AI/ML techniques, organizational governance and sustainable finance in a manner that is both technically possible and socially acceptable [16].

However, also in academic research ESG integration in a digitalized industrial environment is a rather young field of study. Many of the actual studies only analyses a single technology or sustainability aspect separately rather than looking into combined synergies. The relative sustainability of the individual interventions is rarely supported by empirical evidence. Comparative analysis across sectors, countries and firm size is scarce. The resulting complication arising from plural stakeholders competing around what are sustainability priorities is less well served by theory.

This extensive review has simultaneously pursued a number of related aims which have set about addressing defined areas of scarcity in understanding:

- Systematically review the recent literature on ESG integration in the context of Industry 4.0 and 5.0, emphasizing key themes, research methodologies, and empirical results.
- Link ESG dimensions and corresponding sustainability outcomes to specific digital technologies, clarifying pathways through which technological capabilities turn into measurable effects.
- Study implementation blueprints, operational best practices and key success factors that allow companies to efficiently implement ESG-focused digital solutions across a wide and varied range of operational settings.
- Articulate key challenges, barriers and limitations to scaling up and adopt the model more broadly, including technical, economic, organizational and ethical issues.

This study provides a number of important implications for theory and practice. In theory, it contributes to our knowledge of the intricate interrelations between technological development, environmental sustainability, social justice and governance effectiveness in modern industrial settings. Bridging different views over the technology spheres and sustainability aspects, this paper leads to an integrated framework for analyzing ESG-driven digital transformation. Methodically, it shows structured ways of looking at multidimensional phenomena having technical, environmental, social, governance as well as economic dimensions.

2. Methodology

This systematic literature review applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) which aims to ensure diligence, data transparency and replicability in the assessment of already published studies at the integration of Industry 4.0/5.0 technologies with environmental, social and governance. Fig. 1. shows the framework for eligibility criteria based on PRISMA Protocol. The systematic review methodology was applied through three main stages including identification, screening and inclusion with their dedicated criteria and approach. The identification stage aimed for an exhaustive search of the literature from a range of databases and registers in order to capture all relevant work. During the screening stage, predetermined inclusion and exclusion characteristics were applied to screened records. The screening phase was followed by a detailed evaluation of full texts to ascertain final eligibility for synthesis.

In the identification phase, extensive searching was performed in electronic databases such as Web of Science, Scopus, IEEE Xplore, ScienceDirect, ACM Digital Library and Google Scholar. Boolean operators were used to combine search strings of keywords on Industry 4.0 and 5.0 technologies, sustainability concepts and ESG frameworks together. Examples of search terms used were those related to AI, ML, big data, blockchain, the Internet of Things (IoT), digital transformation, sustainability, ESG performance, professional activities and environmental maintenance, social responsibility, corporate governance, sustainable development, circular economy, renewable energy, green finance, supply chain sustainability. The search was limited to peer-reviewed journal articles, conference proceedings, and authoritative reports from 2010 to 2024 so as not to miss new developments yet also have a larger window of time. This preliminary search resulted in 450 records across databases and a further 12 records from sustainable and technology research specific registers.

Duplicate entries were eliminated systematically by reference management software followed by manual examination leaving 219 duplicates to be excluded prior to third stage screening. Title and abstract screening were carried out automatically for an initial relevance assessment, 4 records being excluded as ineligible due to evident lack of fit with the research goal. Another 2 records were excluded for other reasons such as retraction notice and language restrictions. After these initial filtering steps, 237 distinct records were included for full text screening. Screening included a first step in which titles, abstracts and key words were systematically analyzed based on pre-established inclusion criteria. Records had to have significant substance and focus on application of Industry 4.0 or 5.0 technologies to sustainability or ESG fields, original research or substantive conceptual development, methodological rigor appropriate to the study design. This yielded 123 records excluded for limited relevance to the precise study objective, while 114 reports were targeted for full-text retrieval. Three reports were unable to be retrieved after thorough attempts because of unavailability or incomplete publication details.

Detailed full text screening for eligibility was done on 111 of the retrieved reports. This evaluation was also strict in terms of providing value for understanding the technology-ESG links, methodological quality and relevance to the aims of the review. Through this strict selection process, 14 reports were excluded, 7 studies did not contain a clear emphasis on AI or digital technologies which are related to this field as main element, while 4 studies addressed issues outside the scope of interest, and 3 other studies predated our timeframe or present outdated technological contexts. This filtering gave 91 studies that met all the inclusion criteria for the comprehensive review synthesis. These 91 core studies were taken through the final step of inclusion along with incorporation of an additional 6 reports found by forward and backward citation search in the included reports. Assessment of quality appraised methodological rigour, explicit reporting and contribution to theoretical or practical knowledge, but all included papers met the minimum quality criteria applied prior to inclusion. This method leads to an inclusive and unbiased transparent coverage of the research terrain, which helps establish robust ground for conceptualizing the state-of-art knowledge integration not only to identify gaps but also inform future ecology directions for research in Industry 4.0 and 5.0 around sustainability from ESG driven practices.

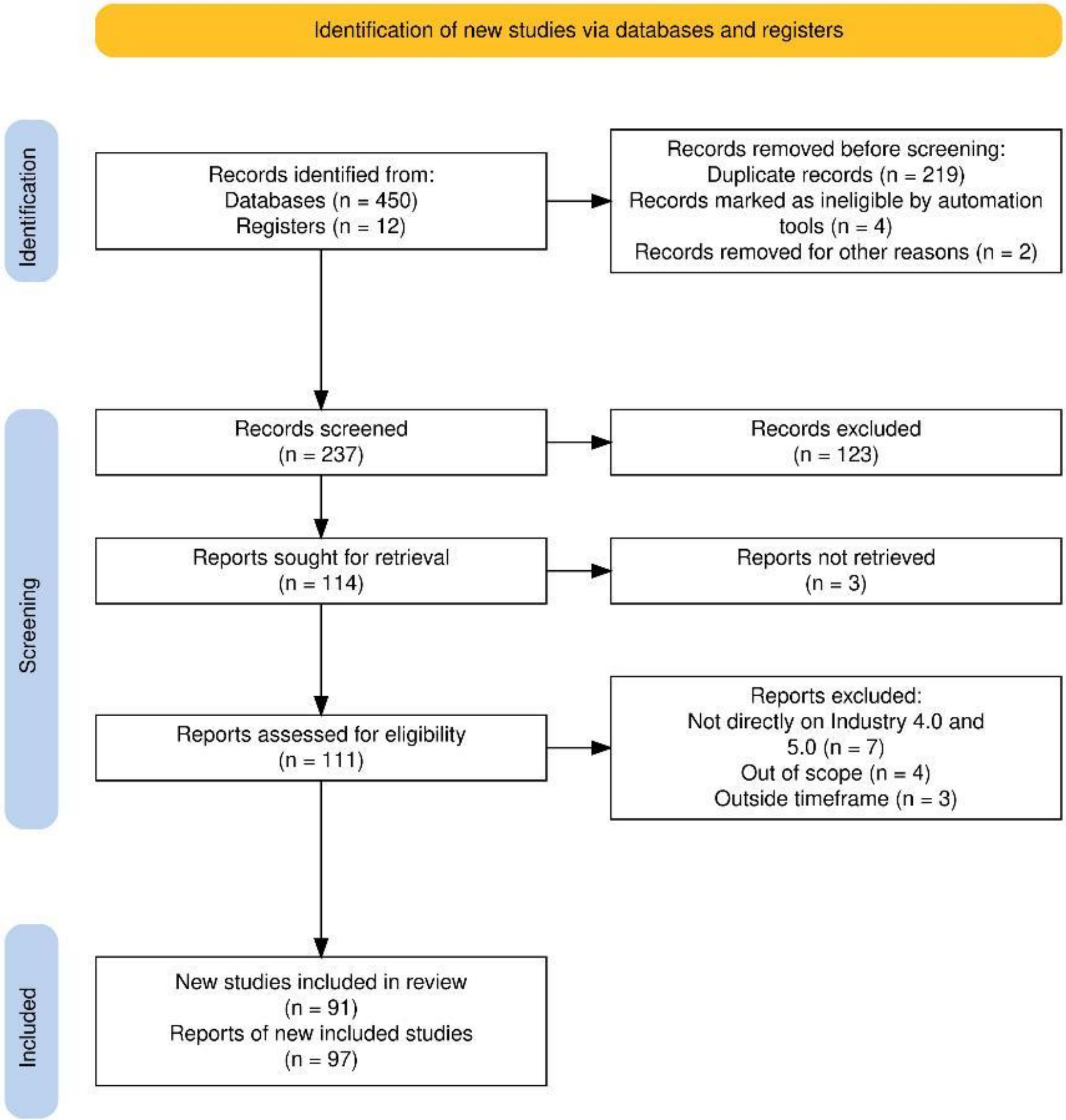

Fig. 1. Framework for eligibility criteria based on PRISMA Protocol

3. Results and discussions

Co-occurrence analysis of the keywords in literature

Three connections are clearly visible “artificial intelligence," "sustainability" and "ESG”, around a dense core with connection to operational technologies, governance issues and performance consequences. Fig. 2 shows the co-occurrence analysis of the keywords in literature. This shows Industry 4.0 and 5.0 is characterized as the connections between corporate sustainability and demonstrable ESG returns. The dominant integration at the center is “artificial intelligence.” It co-occurs with “machine learning,” “big data” and “digital transformation,” and extends “sustainable development goals”, “performance” and ‘information management’. This suggests the AI as not just a tool but the enabling infrastructure for sensing, predicting and optimizing sustainability impacts across industrial systems in a move from descriptive reporting toward prescriptive automated decisioning that is anticipated with Industry 4.0 and human-centric Industry 5.0. The red group near “ESG” groups ideas about governance and disclosure “sustainability reporting,” “corporate governance,” “governance approach,” “corporate social responsibility” and “ESG performance.” Connections from this cluster to the AI indicate a focus in the field on analytics-enabled reporting, assurance and risk management. links to “innovation” and “bibliometric analysis”.

The green group shows operational and techno-economic triggers i.e., 'big data,' 'investments,' 'supply chains,' 'risk assessment,' etc. This group shows the operationalization of ESG by firms using Industry 4.0 tooling in logistics and manufacturing, treating capital allocation and risk as part of the same data-centric workflow at once. The "climate change" and "ethics" suggest that environmental exposure and normative values are being baked in to algorithmic and investment decisions. The blue community focuses on impacts and organization "sustainable development goals," "social aspects," "information management," "corporate sustainability" and "performance." It connects to "machine learning" and "performance," meanwhile, suggests that models and metrics will be utilized across scales, not only to assess environmental benefits but also to measure social value creation, in line with Industry 5.0's people-centered focus. A yellow decision-infrastructure group covers the fields of "decision making," "internet of things," "blockchain," "decentralized finance (DeFi)," "green finance," and" financial markets." This represents increasing demand for traceability and transparency, IoT and blockchain, provenance and real-time monitoring, combined with new ways of financing that direct capital into verified sustainable operations, critical enablers to scale ESG within value chains.

Bridging terms, playing the role of bridges between technology, governance and impact clusters in the entire network, includes "digital transformation", "supply chains", "investments", "risk assessment", and "performance". Their position illustrates the classic research paradigm: AI/IoT gather and structure data; digital transformation embeds analytics in workflows, supply chain applications surface material risks and opportunities, governance and reporting transform those into ESG disclosures; finance allocates capital based on performance signals. The co-occurrence structure presents an AI-drive data-to-disclosure pipeline that bridges Industry 4.0's technologies with Industry 5.0's human and society-perception work. The literature is moving to a unified perspective in which enhanced analytics, reliable data infrastructure and mechanisms of governance taken together are instrumental to ESG performance that can be quantified for industrial ecosystems.

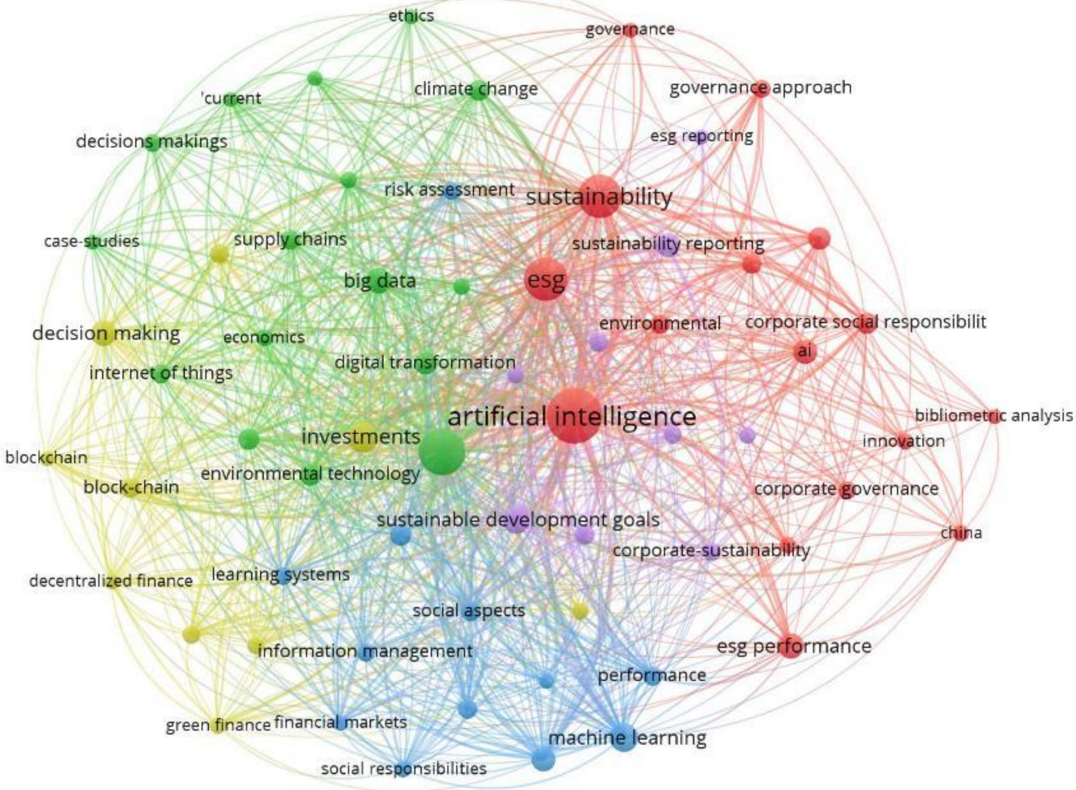

Fig. 2 Co-occurrence analysis of the keywords in literature

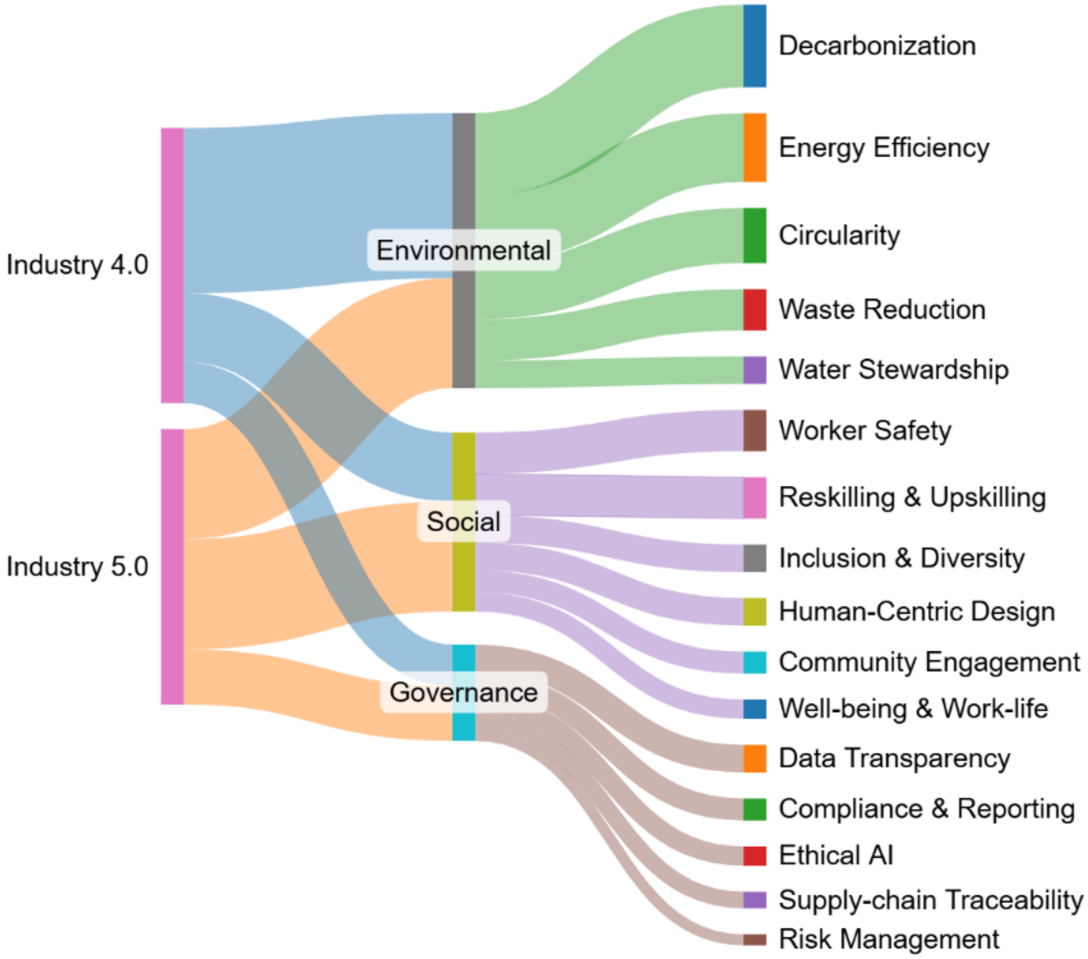

Fig. 3 Mapping of Industry 4.0/5.0 with ESG pillars

This Sankey map (Fig. 3) illustrates how Industry 4.0 and Industry 5.0 impact the three ESG pillars into specific sustainability outcomes. The left side starts from a technology-driven revolution in Industry 4.0 and a human-centered approach in Industry 5.0. On the right we have Industry operations and digital trade ecosystem of Industry beyond. All their streams flow to the right towards Environmental, Social and Governance (ESG). It shows that every industrial strategy links through these three areas simultaneously, not just one. Industry 4.0 is about data-driven automation: digital twinning, IoT-enabled robots and machine learning that boost operational performance. From an environmental point of view, those gains from "datafication" need to equate not just to lower resource use, but also to lower emissions.

Artificial intelligence and machine learning applications

AI and analytics are changing everything from environmental monitoring, to resource efficiency, to predictive maintenance [16]. Machine-learning systems can uncover patterns in sensor and operational data that would be hard for people to discern by analyzing large amounts of such data [16,17]. Deep learning, in particular, is good at identifying complex patterns like sniffing out defects, forecasting demand for a product or flagging anomalies [12,18-20]. One of the best use cases for this type of data is preventive maintenance. Time-based maintenance is typically either done too late to prevent failures or premature. AI-based condition monitoring processes the live sensor data to develop estimates of remaining useful life, and also concepts of the likelihood that a component will be damaged very accurately [21-23]. This makes it possible to avoid scheduling maintenance when it may not be needed, extending asset life, minimizing downtime and reducing total cost of ownership often significantly and eliminating waste through the replacement of parts too soon [24,25]. Energy conservation is also another a significant use case. Factories use a lot of energy. Models based on machine learning are used to process consumption data for equipment, processes and ambient conditions to identify opportunities for savings. RL controllers have shown to optimize process variables for higher efficiency, while maintaining adequate product quality [26-28]. For both print processes, one can usually expect two-digit reduction in energy consumption at scale, as well as reduced operating cost and CO_2 emissions.

Internet of things and real-time monitoring

The Internet of Things (IoT) is changing the way we measure and improve sustainability [29-31]. It offers real-time detailed visibility into physical processes, environmental conditions and asset performance. Massive data streams are produced up to minutes/hour/day of continuous sensor networks effectively allowing in traditionally inefficient and atypical behavior as well as predicting potential failure long before the event.. This immediacy means we can act proactively rather than reacting to problems after they have arisen handling problems before they become problems affecting the long-term environment and operations. There are also smart building systems which is among the IoT applications for sustainability [3,32,33]. People Counter and Temperature and Humidity and Light Sensors to automatically manage response on occupancy, temperature, humidity and light by adjusting the controls to comforts level ensuring efficiency [4,34-36]. Occupancy patterns are learnt by building management systems to condition spaces in advance of arrival, but without wasting energy where there is no occupancy. It can be applied to manufacturing equipment, utility system and environmental monitoring in IoT. Vibration sensors achieve early warning of bearing wear and impending failure. Transducers help make fluid systems energy efficient by controlling pressure. Flowmeters keep track of the water and compressed air that you use, at the same time discovering leaks or machinery that is not operating efficiently when it comes to percentage of maximum capacity being used by a given operation. Combined, these sensors give a complete, up-to-date representation of operations in real-time making continuous optimization possible. Supply chain visibility is expanded through IoT tracking devices: Shipment tracking fueled by GPS ensures optimal routing and quicker time in transit, as temperature and humidity monitoring safeguards perishable goods from spoilage [37-40]. Amulet's condition-monitoring tools reveal signs of rough handling or inadequate warehousing so problems can be corrected promptly. This degree of visibility to the part and subassembly level provides all contributors better coordination tools, and is already beginning to deliver tangible value by reducing waste stemming from inefficiency.

Environmental monitoring networks may be used to monitor air or water quality, sound levels and other environmental conditions as indicators of the environment. Spatial coverage Deployed sensors provide spatial coverage that is unachievable with conventional surveillance methods. Streamed data permits real-time reaction to pollution or environmental degradation [4,41,42]. Long–term data collection can identify trends that may support environmental management and regulatory compliance. Citizen-based sensing projects involved people in caring about their surroundings and spread access to environmental information. IoT technology is used in workplace safety apps for hazard detection and employee protection. Sensing wearables track physiological signals indicating processes such as heat stress, fatigue or toxic exposure. Environmental sensors detect unsafe gas levels, extreme temperatures or structure stability. Collision avoidance is generally the purpose for of proximity detection systems between workers and mobile equipment. Emergency response systems help evacuate and provide medical aid to the wounded. These functions ensure worker welfare, while indicating organizational dedication to social sustainability.

Blockchain technology and transparency

For sustainability, blockchain tech can solve some very serious transparency and trust problems. Conventional configurations depend on centralized institutions that may be easily targeted for manipulation, mistakes or weaknesses [43-45]. By encrypting and storing data in a decentralized manner, blockchain makes records unmodifiable and transparent for those who have access to it, providing an opportunity to be accountable and not allow fake claims [9,46-48]. This feature is especially important for supply chain traceability, certification matching, and sustainability reporting when credibility equals action. Supply chain transparency is the leading use case of blockchain for sustainability. Complex global supply chains consist of hundreds of middlemen, it is almost impossible to trace where a product comes from, or if it has been ethically sourced [49-50]. Blockchain makes it possible to trace the end-to-end history of transaction and custody transfers without any alteration. Customers scan the product code and can view the full traceability with all certificates, raw materials used, production sites and transport routes [51,52]. This transparency fights against counterfeits and allows decisions to support ethical producers. Blockchain-based verification systems such as Blockcerts help to guarantee that the credential being verified is not counterfeit. There are many other sustainability certifications such as organics, fair trade, environmental etc. But the market for fake ones is booming, casting a shadow on the real deals. In blockchain powered systems, records of the certifications are stored in an immutable way so that it can be verified instantly. Smart contracts will validate certifications automatically which means that no expired or fake credentials are able to flow along supply chains.

Digital transformation and organizational change

Sustainability must also be built into organizational design. Siloed departments prohibit the cross-functional cooperation needed for systems-level solutions [53-56]. Hiring a sustainability operations head to coordinate across operations, procurement, marketing and finance can tie initiatives together. Multidisciplinary teams must pool heterogenous skills to address complex problems under time constraints [57-59]. When managed well, matrix structures combine functional depth with project ability, fostering complete solutions over point fixes. Lastly, fill skills gaps with specific training and strategic hires that will drive investment and impact. Despite demand, there is still a shortage of people with data-analytical skills. Managing change ensures a smooth adoption of technology. To have sustainability literacy is to equip your staff with an understanding of how people interact with nature Learning is hastened by joint ventures with academic institutions, technology providers and industry associations. Culture: Cultures of continuous improvement promote experimentation, failure-based learning and sharing knowledge.

Culture change is the most difficult and vital work of all. Compliance responsibility has to be converted into strategic opportunity [6,60-62]. Staff of all levels need to be empowered to find and follow through on changes. Innovation mindsets replace risk-averse cultures. Long-term thinking supersedes short-term pressure. Collaborative approaches replace competitive behaviors. These changes in culture take time, constant messaging, and positive reinforcement through organizations and informal networks. Business model innovation uses digital capabilities to develop novel value propositions. Wasteful take-make-dispose economies being substituted for circular ones. In product-as-a-service sales, the incentives shift from volume to value. Platform-based business models link sustainability actors to enable collaboration. Digital platforms consolidate sustainable goods making it easy for customers to find them. These innovative models reveal that profitability and sustainability are complementary, rather than contradictory, when the business logic is right.

Sustainable finance and green investment

A financial sector reformation is necessary for taking sustainable initiatives to scale in economies. Decisions on the allocation of capital influence development paths which technology, business model or practice is successful [63-65]. Classical finance preferred the short-term returns and did not fully consider long-term environmental and social factors. Sustainable finance incorporates ESG factors in investment analysis, thereby acknowledging that the dimensions of sustainability impact on risk and return profiles. This transition is a reflection of the greater moral purpose as well as an economically driven acknowledgement that risky behaviors are not financially sustainable. Green bonds direct investment to projects that benefit the environment such as renewable energy installations, energy efficiency upgrades and sustainable transport infrastructure. Table 1 summarizes the key technologies, their applications across ESG dimensions.

Supply chain sustainability and resilience

Automatic software can monitor compliance in areas such as general waste, emissions and workplace incidents. Underperforming supplier should get improvement instructions from relationship. This scrutiny also encourages improvements of suppliers' ESG performance, thereby downcascading sustainability expectations across value chains [65-67]. From collaborative point of view, the buyer and supplier can share information and collaborate to improve together on such platforms. Local suppliers receive training, technical assistance, and financial support to improve their capacity. Shared savings promote incentive alignment, so that both parties share in efficiency gains. Projects formed by industry collaborations combine resources to solve systemic problems which no one company has the capacity to solve. Pre-competitive collaboration on sustainability standards can guard against races to the bottom and level playing fields. Table 1 shows the key technologies, their applications across ESG dimensions.

Table 1 Provides key technologies, their applications across ESG dimensions.

Sr. No.	Technology/Tool	ESG Application	Implementation Approach	Key Challenges and Opportunities
1	Artificial Intelligence and Machine Learning	Predictive maintenance, energy optimization, quality control, demand forecasting, environmental monitoring	Deploy sensor networks, train ML models on historical data, integrate with existing systems, establish feedback loops	Requires large datasets, model interpretability issues, high initial costs, but offers 30-45% efficiency gains
2	Big Data Analytics	Sustainability reporting, carbon footprint calculation, risk assessment, performance benchmarking, supply chain visibility	Implement data warehouses, establish data governance, develop analytics dashboards, automate reporting workflows	Data quality challenges, privacy concerns, integration complexity, enables evidence-based decision making
3	Internet of Things	Real-time monitoring, smart buildings, industrial equipment tracking, environmental sensing, workplace safety	Install sensor networks, ensure connectivity infrastructure, develop edge computing capabilities, establish data protocols	Cybersecurity vulnerabilities, device management complexity, substantial connectivity value through 24/7 monitoring
4	Blockchain Technology	Supply chain traceability, certification verification, carbon credit trading, transparent reporting, circular economy tracking	Select appropriate blockchain platform, design smart contracts, ensure stakeholder participation, integrate with existing systems	Scalability limitations, energy consumption concerns, regulatory uncertainty, immutable transparency benefits
5	Cloud Computing	Scalable data storage, collaborative platforms, distributed processing, backup and recovery, analytics infrastructure	Migrate to cloud platforms, implement security measures, optimize costs, ensure compliance with data regulations	Vendor lock-in risks, data sovereignty issues, significant scalability and cost efficiency advantages
6	Digital Twin Technology	Process optimization, scenario planning, virtual testing, asset lifecycle management, predictive modeling	Create virtual models, establish real-time data feeds, develop simulation capabilities, integrate with operational systems	High development costs, modeling complexity, enables risk-free experimentation and optimization

7	Robotic Process Automation	Automated reporting, compliance monitoring, data entry elimination, workflow optimization, consistency improvement	Identify automation opportunities, develop bot workflows, test thoroughly, implement governance frameworks	Process dependency, limited cognitive capabilities, delivers 60-80% time savings on routine tasks
8	Advanced Sensors	Emissions monitoring, water quality tracking, energy consumption measurement, waste tracking, air quality assessment	Select appropriate sensors, ensure calibration protocols, establish data collection systems, validate accuracy	Maintenance requirements, calibration needs, harsh environment challenges, precise measurement capabilities
9	5G Connectivity	Enhanced IoT capabilities, remote operations, autonomous systems, real-time control, massive device connectivity	Upgrade network infrastructure, redesign applications for low latency, ensure security, manage bandwidth	Infrastructure investment requirements, coverage limitations, enables transformative real-time applications
10	Edge Computing	Local data processing, reduced latency, enhanced privacy, bandwidth optimization, autonomous operations	Deploy edge devices, distribute processing logic, ensure synchronization, implement security measures	Device management complexity, limited processing power, critical for remote and real-time applications
11	Computer Vision	Defect detection, safety monitoring, environmental surveillance, waste sorting, biodiversity assessment	Collect training images, develop detection models, integrate with cameras, establish quality thresholds	Lighting sensitivity, occlusion handling, achieves 98%+ accuracy in controlled environments
12	Natural Language Processing	Sentiment analysis, regulatory compliance, report generation, document analysis, stakeholder feedback processing	Collect text corpora, train language models, develop classification systems, validate outputs	Context understanding limitations, language specificity, enables automated insight extraction from text
13	Predictive Analytics	Demand forecasting, failure prediction, risk modeling, trend identification, scenario planning	Gather historical data, build statistical models, validate predictions, integrate into planning processes	Requires quality historical data, model validation challenges, improves planning accuracy by 25-40%
14	Augmented Reality	Training programs, maintenance guidance, remote assistance, safety procedures, process visualization	Develop AR applications, deploy AR devices, create content libraries, train personnel	Device cost barriers, user adoption challenges, reduces training time by 30-50%
15	Additive Manufacturing	On-demand production, waste reduction, design flexibility, spare parts optimization, distributed manufacturing	Acquire 3D printers, develop digital inventories, optimize designs for printing, establish quality controls	Material limitations, production speed constraints, reduces material waste by 40-90%

16	Energy Management Systems	Consumption monitoring, load optimization, renewable integration, demand response, cost management	Install smart meters, implement control systems, establish baselines, set optimization targets	System integration complexity, change management needs, achieves 15-30% energy savings
17	Satellite Monitoring	Deforestation tracking, land use changes, emissions verification, disaster response, environmental assessment	Access satellite data feeds, develop analysis algorithms, establish change detection protocols, integrate with GIS	Cloud cover limitations, resolution constraints, provides unprecedented global monitoring coverage
18	Collaborative Platforms	Stakeholder engagement, supply chain coordination, knowledge sharing, project management, transparency	Select platform software, onboard participants, establish governance, integrate with workflows	Adoption barriers, information overload risks, enhances coordination and reduces communication overhead
19	Simulation Software	Process optimization, what-if analysis, training environments, design validation, risk assessment	Develop models, validate against reality, establish scenarios, integrate with decision processes	Modeling complexity, computational requirements, enables risk-free exploration of alternatives
20	Mobile Applications	Field data collection, workforce management, customer engagement, sustainability reporting, awareness campaigns	Develop user-friendly interfaces, ensure offline capabilities, implement security, integrate with backend systems	Device diversity challenges, connectivity dependencies, provides immediate data access and engagement
21	Quantum Computing	Complex optimization, materials discovery, climate modeling, risk analysis, cryptography	Partner with quantum providers, identify suitable problems, develop quantum algorithms, prepare for future capabilities	Limited current availability, requires specialized expertise, promises revolutionary capabilities for specific problems
22	Autonomous Systems	Automated inspections, efficient transportation, precision agriculture, warehouse optimization, hazardous task handling	Develop autonomy algorithms, ensure safety systems, establish operational protocols, address liability	Safety concerns, regulatory uncertainty, ethical considerations, substantial efficiency and safety improvements
23	Smart Contracts	Automated compliance, transparent transactions, conditional payments, certification management, carbon credit trading	Develop contract logic, ensure legal validity, test thoroughly, establish dispute resolution	Immutability challenges, legal recognition issues, eliminates intermediaries and ensures transparent execution
24	Biometric Systems	Access control, time tracking, safety compliance, identity verification, personalized experiences	Deploy biometric devices, ensure data protection, establish consent protocols, integrate with security systems	Privacy concerns, accuracy variations, spoofing risks, enhances security and eliminates credential management
25	Virtual Reality	Immersive training, design reviews, stakeholder	Acquire VR equipment, develop immersive content, establish safety	Motion sickness issues, high equipment costs, creates

		engagement, hazard simulation, collaborative workspaces	protocols, measure effectiveness	compelling experiences and effective training environments
26	Geospatial Analytics	Site selection, logistics optimization, environmental impact assessment, resource mapping, infrastructure planning	Integrate mapping data, develop spatial models, establish visualization capabilities, validate accuracy	Data availability variations, accuracy limitations, provides critical location-based insights
27	Cybersecurity Solutions	Data protection, system integrity, compliance assurance, threat detection, incident response	Implement security frameworks, deploy monitoring tools, train personnel, establish incident protocols	Evolving threat landscape, complexity challenges, essential for protecting digital assets and ensuring trust
28	Chatbots and Virtual Assistants	Customer service, employee support, information access, automated responses, engagement enhancement	Develop conversational models, integrate with knowledge bases, test interactions, measure satisfaction	Understanding limitations, inappropriate response risks, provides 24/7 availability and immediate responses
29	Data Visualization Tools	Dashboard creation, trend communication, performance monitoring, stakeholder reporting, insight discovery	Select visualization platforms, design effective displays, establish update protocols, train users	Information overload risks, misinterpretation potential, makes complex data accessible and actionable
30	Integration Platforms	System connectivity, data synchronization, workflow automation, legacy system modernization, API management	Map integration requirements, develop connectors, ensure data quality, establish governance	Technical complexity, maintenance overhead, essential for enabling digital ecosystem functionality

Circular supply chains waste by using a closed-cycle of materials. Recycling reverse logistics collect already used products for remanufacturing, refurbishing, or recycling. Design for disassembly allows material recovery at the end-of-life.

Renewable energy integration and smart grids

The technologies that drive our battery storage systems have progressed significantly in recent years, and the costs to these technologies continue to drop exponentially as they become increasingly more efficient [3,65-67]. Large scale storage acts as a balance in place of the peaking plants or dispatchable generators, allowing more variable input to be used for baseload. In demand side programs, the pattern of electricity consumption is adjusted according to renewable generation. Smart appliances modify operation as directed by price signals decoupled from grid status. Factory floors shift-energy-intensive processes to when renewable generation is at its peak. The electric vehicle charging load peaks during sunny or windy hours when the renewable generation is outpacing demand. These demand side management techniques decrease the amount of required peak generation and reduce consumer costs.

Predictive analytics are vital to optimal renewable energy management thanks to better forecasting. Machine learning algorithms analyze weather developments and historical information in real-time, predicting the output of generation hours or days before. This way of production gives operators some latitude in operation resource dispatch [68-70]. The enormous capacity represented by distributed energy resources like rooftop and small wind also needs co-operation of this kind. As large single sites, virtual power plants summon these distributed assets to proper grid operation. During disturbances, microgrids can separate from the main grid and still supply local power. But such systems, when used as a form of control strategy so that between locally generated electricity through renewable sources and storage by the load itself in which it incorporates integration with renewable generation and reserves of power convenient to carry nearby loads may enable isolated areas to withstand blackouts for hundreds of years. As critical facilities for hospitals, first responders, and shelters, microgrids increase resilience. And with the help of microgrids, isolated and impoverished island communities as well as distant villages can use renewable electricity to replace their consumption of expensive diesel fuel. The location and consumption of power can be optimized through energy management solutions directed at specific plants.

Challenges and barriers

Making multiple connections multiplies the cyber vulnerabilities which threatens to make organizations victims of ransomware, data loss and industrial espionage. These technical difficulties require external help from consultants and technology suppliers, add to time-effectiveness and result in dependency. Resistance organizationally is expressed through various ways [55,71-73]. The threat of change to set roles and hierarchies. Cultural momentum keeps us doing things the way we have always done them, even when they're stupid or unworkable. Other types of Short-term financial pressures lead to the focus on short term profit over long-term sustainability investments. Risk aversion does not promote trying new methods. Organizational silos do not facilitate the cross-functional collaboration needed for systemic sustainability efforts. If senior executives champion change, but middle management resists, implementation is already compromised. Resistance can only be removed by manumission in a recurring effort across cultural, political and structural aspects. Table 2 shows how ESG principles and digital technologies manifest.

Table 2 shows how ESG principles and digital technologies manifest

Sr. No.	Industry Sector	Key ESG Priorities	Digital Technology Applications	Implementation Focus and Outcomes
1	Manufacturing	Carbon emissions reduction, waste minimization, worker safety, supply chain transparency, circular economy	AI-powered predictive maintenance, IoT energy monitoring, digital twins for process optimization, blockchain supply tracking	Smart factories reduce energy by 25%, predictive maintenance cuts downtime 30%, real-time safety monitoring prevents incidents
2	Energy and Utilities	Renewable integration, grid reliability, emissions tracking, demand management, customer engagement	Smart grids with AI optimization, IoT smart meters, predictive analytics for demand, blockchain energy trading	Renewable penetration increased to 40%, demand response programs reduce peak load 15%, virtual power plants aggregate distributed resources
3	Transportation and Logistics	Fleet emissions reduction, route optimization, safety improvement, alternative fuels, last-mile efficiency	AI route optimization, IoT fleet tracking, electric vehicle integration, autonomous delivery systems	Route optimization reduces emissions 20%, predictive maintenance improves safety, EV fleets lower operational costs 30%
4	Agriculture and Food	Sustainable farming, water conservation, supply chain traceability, food safety, waste reduction	Precision agriculture with IoT sensors, AI crop monitoring, blockchain farm-to-table tracking, satellite monitoring	Precision farming reduces water use 30%, AI crop monitoring improves yields 25%, blockchain ensures food provenance

5	Retail and Consumer Goods	Sustainable sourcing, packaging reduction, ethical supply chains, consumer engagement, circular models	AI demand forecasting, blockchain authenticity verification, IoT inventory optimization, mobile engagement apps	Demand forecasting reduces waste 35%, blockchain combats counterfeiting, product-as-service models emerge
6	Financial Services	Sustainable investing, climate risk assessment, green finance, financial inclusion, transparent reporting	AI credit risk models with ESG factors, big data climate analytics, blockchain green bonds, robo-advisors for ESG	ESG portfolios outperform traditional benchmarks, climate risk integration improves lending decisions, green bond market grows 300%
7	Healthcare	Energy efficiency, medical waste management, equitable access, supply chain ethics, community health	AI diagnostic tools, IoT hospital energy management, telemedicine platforms, supply chain blockchain	Energy management reduces costs 20%, telemedicine expands rural access, blockchain ensures medication authenticity
8	Construction and Real Estate	Green buildings, material efficiency, site safety, lifecycle assessment, sustainable urbanization	BIM with sustainability modules, IoT building management, drones for monitoring, AR for safety training	Smart buildings reduce energy 40%, BIM optimization cuts material waste 30%, IoT monitors structural health
9	Mining and Extractives	Environmental rehabilitation, water management, community relations, worker safety, biodiversity protection	Autonomous equipment for safety, IoT environmental monitoring, satellite land tracking, AI resource optimization	Autonomous systems improve safety 60%, real-time monitoring prevents environmental incidents, satellite tracking ensures rehabilitation
10	Chemicals and Pharmaceuticals	Process safety, emissions control, responsible innovation, waste treatment, sustainable chemistry	AI process optimization, IoT leak detection, digital twins for safety, blockchain clinical trial tracking	Process optimization reduces emissions 25%, predictive maintenance prevents releases, digital twins test scenarios safely
11	Telecommunications	Network energy efficiency, e-waste management, digital inclusion, data privacy, infrastructure sharing	AI network optimization, renewable-powered towers, IoT energy management, virtualization technologies	Network optimization reduces energy 30%, tower sharing decreases infrastructure footprint, renewable integration accelerates
12	Textiles and Apparel	Sustainable materials, water reduction, supply chain ethics, circular fashion, chemical management	Blockchain supply transparency, AI quality control, IoT water monitoring, digital product passports	Blockchain verifies ethical sourcing, AI reduces defects 40%, water monitoring cuts consumption 35%, digital passports enable recycling
13	Aviation and Aerospace	Fuel efficiency, emissions reduction, noise management, safety enhancement, alternative fuels	AI flight optimization, IoT predictive maintenance, biofuel integration, digital twins for design	Route optimization saves fuel 12%, predictive maintenance improves reliability, sustainable aviation fuel adoption grows
14	Hospitality and Tourism	Energy efficiency, water conservation, waste reduction, local	Smart building systems, IoT resource monitoring, mobile guest engagement, AI demand forecasting	Smart systems reduce energy 35%, IoT cuts water use 25%, mobile apps enhance guest

		engagement, cultural preservation		experience while promoting sustainability
15	Education	Campus sustainability, digital access, inclusive learning, research impact, community engagement	Learning management systems, IoT campus energy management, virtual labs, AI personalized learning	Energy management cuts costs 30%, digital platforms expand access, virtual labs reduce resource consumption
16	Media and Entertainment	Production efficiency, digital distribution, diversity representation, content responsibility, carbon footprint	Cloud-based production, AI content analysis, streaming optimization, virtual production technologies	Digital distribution reduces physical media waste, virtual production cuts set material use, AI ensures responsible content
17	Shipping and Maritime	Emissions reduction, ballast water management, safety improvement, route optimization, alternative fuels	AI route planning, IoT engine monitoring, satellite navigation, autonomous vessels	Route optimization reduces emissions 15%, predictive maintenance prevents spills, IoT ensures environmental compliance
18	Waste Management	Circular economy enablement, sorting efficiency, emissions reduction, hazardous waste tracking, community engagement	AI-powered sorting, IoT bin monitoring, route optimization, blockchain waste tracking	AI sorting improves recovery rates 50%, route optimization cuts collection emissions 20%, blockchain ensures compliance
19	Water Utilities	Leak reduction, quality monitoring, equitable access, efficiency promotion, infrastructure resilience	IoT sensor networks, AI leak detection, smart meters, predictive maintenance	AI detects leaks reducing losses 40%, smart meters encourage conservation 20%, predictive maintenance prevents failures
20	Automotive	Electric vehicle transition, circular design, supply chain sustainability, safety innovation, shared mobility	AI battery management, IoT vehicle connectivity, blockchain battery provenance, simulation for design	EV platforms eliminate tailpipe emissions, IoT enables predictive servicing, blockchain tracks responsible sourcing
21	Technology and Software	Data center efficiency, e-waste management, algorithmic fairness, digital inclusion, sustainable AI	AI workload optimization, renewable energy integration, efficient algorithms, edge computing	Data center PUE improves to 1.1, renewable energy powers 75% of operations, efficient AI reduces computational waste
22	Forestry and Paper	Sustainable harvesting, certification verification, reforestation, biodiversity protection, water management	Satellite monitoring, blockchain certification, IoT equipment tracking, AI growth modeling	Satellite monitoring prevents illegal logging, blockchain verifies sustainable sourcing, AI optimizes harvest planning
23	Beverages and Brewing	Water stewardship, packaging sustainability, sustainable agriculture, energy efficiency, community impact	IoT brewing optimization, water recycling systems, blockchain ingredient tracking, renewable energy	Brewing optimization reduces water use 40%, renewable energy powers production, blockchain ensures ingredient quality
24	Pharmaceuticals Distribution	Cold chain integrity, counterfeit prevention, equitable access, waste	IoT temperature monitoring, blockchain authentication, AI demand	IoT ensures product integrity, blockchain eliminates counterfeits, AI

		reduction, ethical marketing	forecasting, route optimization	optimizes inventory reducing expiry waste
25	Sports and Recreation	Facility sustainability, event impact reduction, inclusive access, athlete welfare, legacy planning	Smart venues with IoT, renewable energy systems, virtual experiences, wearable safety tech	Smart venues reduce energy 45%, virtual experiences expand access, wearables protect athlete health
26	Defense and Security	Environmental stewardship, energy security, technology responsibility, veteran support, infrastructure resilience	Renewable energy for bases, AI cybersecurity, efficient logistics, satellite monitoring	Renewable installations enhance energy security, AI protects critical systems, efficient logistics reduce footprint
27	Insurance	Climate risk assessment, sustainable underwriting, disaster response, financial inclusion, transparent claims	AI risk modeling, satellite damage assessment, big data climate analytics, blockchain claims processing	AI improves risk assessment accuracy 40%, satellite enables rapid disaster response, blockchain accelerates claims
28	Public Sector	Sustainable infrastructure, citizen services, transparent governance, climate adaptation, social equity	Smart city platforms, open data portals, IoT infrastructure monitoring, AI service optimization	Smart city technologies improve efficiency 30%, open data enhances transparency, IoT enables predictive maintenance
29	Professional Services	Sustainable operations, client advisory, thought leadership, diversity, carbon neutrality	Virtual collaboration tools, cloud services, AI-powered insights, carbon tracking platforms	Virtual collaboration reduces travel emissions 60%, cloud services minimize physical infrastructure, carbon neutrality achieved
30	Life Sciences Research	Ethical research, sustainable labs, open science, reproducibility, societal benefit	AI drug discovery, virtual experiments, open data platforms, cloud-based collaboration	AI accelerates discovery timelines 50%, virtual experiments reduce resource use, open platforms enhance reproducibility and accessibility

Opportunities and future directions

The solution of optimizing logistics for a large network might be solved. Molecular planning can revolutionize the development of carbon capture technology [26,74-76]. Create your own Quantum computers are still very young, but continual strides suggest transformative potential within the next ten years. Edge computing supports real-time processing near data sources, which minimizes the demand for latency and bandwidth with enhanced privacy [77-79]. On-device analytics are directly integrated into the components and systems of manufacturing equipment enabling instantaneous decision making. They are stand-alone and function without the need for a center of control. With a smaller amount of data transmission, energy consumption can be saved. These functionalities are especially helpful for situations where internet connectivity is poor, making it hard for poorer providers to gain access to the kind of complex analytics that have always been accessible online and via cloud computing. Digital twins are the virtual avatar of a physical asset, process or system that allow advanced simulation and optimization. Manufacturers simulate production lines testing changes before they ever make them in the real world. Planners model the development of infrastructure to gauge sustainability effects. Energy systems controllers optimize grid operations via digital twins. Supply chain managers simulate various types of disruption to the supply network and analyze appropriate resilience strategies. Such virtual worlds provide the means to experiment and learn, without having to consume resources (e.g. power or bandwidth) in the real world, with the risk of breaking something.

Advances in satellite technology are offering new and unique capabilities for earth observation, which support environmental monitoring. The world's high-res imagery maps rainforest-clearing, urban sprawl and new roads. Spectral analysis is used to determine the health of vegetation and crop productivity. Ecological surveillance is used to monitor GHG levels and air quality [80-83]. Ocean observation monitoring of temperature, currents and marine ecosystems. Such functionalities could facilitate decision-making and the enforcement of environmental law through transparent monitoring. Synthetic biology and biotechnology may provide sustainable solutions to existing materials and processes. Synthetic microorganisms: Engineering biology phages into new gall shape. Crop biotechnology increases the resilience of crops and their nutritional value while decreasing chemical inputs. Cellular agriculture is the future of protein without animal agriculture’s impact on the environment. Petroleum based plastics are being replaced by biodegradable plastics made from renewable resources. They are also examples of biological inventions that can rival digital technology. The sharing economy, novel models of organized consumption enabled by digital platforms also referred to as collaborative consumption, shares assets more effectively and lowers overall resource demands. More and more often, sustainable performance becomes a regulatory duty as well as an innovative possibility. In a carbon pricing system, the negative side-effects of emissions are internalized. Extended producer responsibility shifts end-of-life costs to producers. Mandatory due diligence laws demand human rights and environmental protections throughout the supply chain. Disclosure requirements on sustainability provide transparency and accountability. Green industrial policies direct public investment to environmentally sustainable technologies. Such regulatory moves level the playing field and spur innovation.

4. Conclusions

This review demonstrates that sustainability can evolve from static reporting to an operational capability when Industry 4.0 technologies are guided by the prism of Industry 5.0. Artificial intelligence, machine learning, IOT and blockchain already allow energy optimization, waste reduction, safer workplaces and traceable supply chains; natural-language and graph analytics link unstructured disclosures to attested performance. The most robust advances come through embedding these tools in governance built upon transparency, human well-being and resilience. The key results are that real-time ESG performance is technically feasible within current architectures, that explainable, privacy-preserving and auditable models are necessary for trust and that the ability to associate operational improvements with sustainable finance instruments accelerates diffusion by rewarding actual progress over promises. What it means for managers: Align incentives around material sustainability goals, invest in data and model stewardship and integrate finance and operations so that improvements to ESG inform capital allocation. For policy advocates, the lesson is to keep aligning reporting standards and to acknowledge machine-readable, attested metrics. For researchers, some of the promising venues include autonomous sustainability control with human-in-the-loop safety nets, scalable Scope 3 estimation and uncertainty quantification, fairness and bias mitigation in worker-facing analytics, biodiversity and water footprint modeling as well as architectures that render digital product passports and continuous macro assurance feasible for small suppliers. Industry 5.0 will deliver on its promise when smart systems serve both productivity and dignity, when transparency can be found despite greenwashing, and the benefits of transformation are shared throughout the value chain and among the communities it reaches.

Social impact quantification needs further definition. Such methodological advances could improve accountability and limit the potential for greenwashing. New technologies such as quantum computing, edge computing, digital twins, advanced biotechnology and satellite observation system deserve attention in the context of sustainability relevant applications. System dynamics simulation may enlighten the complicated relationships between technological, economic, social and environmental dimensions. Sustainability problems are characterized as possessing feedback loops, time lags and non-linear interactions which do not lend themselves to a linear analysis. Simulation models would provide the opportunity to explore scenarios and test policies in silico before real world implementation. Focus on the implementation of circular economy. Despite the attractive concept, application in practice is challenging. The business model innovation, the reverse logistics optimization, the product design for circularity and also a change in human behavior to be able complexly decompose circular system type of research. The function of technology in support of circularity, specifically traceability, quality assurance and marketplace coordination should be explored. The former is significantly less addressed than the latter. Study should investigate how ICTs contribute to the eradication of poverty through resilience-building, early-warning systems, adaptive capacity enhancement and vulnerability reduction. Even if successful, the consequences of climate will persist and adaptation capacity is required. The question of just transition also requires deliberation, considering how a transformation towards sustainability affects workers, communities and regions that rely on declining industries. Research needs to examine the promotions and the policy measures for those groups, to guarantee that transitions towards sustainability are inclusive but also do not generate new inequalities.

Author Contributions

NA: Conceptualization, study design, data collection, methodology, software, writing original draft, and writing review and editing. MSR: Data collection, methodology, software, visualization, writing original draft, and writing review and editing.

Conflict of interest

The authors declare no conflicts of interest.

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