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Industry 4.0 and the Environment: A Review of Ecological Implications and Integrated Mitigation Strategies

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A R T I C L E I N F O

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A B S T R A C T

Industry 4.0 transformation offers opportunities to improve resource efficiency and environmental performance, but at the same time creates new ecological burdens through digital energy consumption, critical material needs, e-waste, and rebound effects. This article aims to analyze the positive and negative implications of Industry 4.0 on the environment and formulate integrated mitigation strategies that are relevant to companies and policymakers. The study uses qualitative literature review that is non-systematic, interpretive, and critical by synthesizing 55 verified journal articles published since 2020. Thematic analysis shows that environmental benefits mainly emerge through real-time monitoring, predictive maintenance, process optimization, energy and material efficiency, waste reduction, and strengthening the circular economy. In contrast, computing and communication infrastructure increases the need for electricity, water, hardware, minerals, and end-of-life management, while relative efficiency can be offset by production expansion. The end impact is conditional because it is influenced by energy mix, organizational capabilities, supply chain integration, product design, data governance, regulation, and measurement throughout the lifecycle. This article proposes the avoid–reduce–circularize–decarbonize–verify principle and eight mitigation pillars that link materiality assessments, absolute targets, technology selection, sustainable operations, circularity, decarbonization, governance, and verification. For Indonesia and developing countries, transformation needs to be carried out gradually and inclusively through support for small and medium-sized enterprises, extended producer responsibility, data interoperability, green incentives, and performance-based regulations

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INTRODUCTION

The development of the industrial revolution since the beginning of industrialization has increased production capacity, productivity, and economic prosperity, but at the same time has increased the pressure on natural resources, environmental quality, and ecosystem stability. In the contemporary context, Industry 4.0 marks a fundamental change through the integration of cyber-physical systems, Internet of Things (IoT), artificial intelligence, big data analytics, cloud computing, robotics, and other digital technologies into production processes and value chains. This transformation is no longer just a matter of factory automation, but a socio-technical change that affects the way companies design products, use energy and materials, manage suppliers, and make decisions. Therefore, the relationship between Industry 4.0 and the environment needs to be critically understood because digitalization can be a lever for sustainability, but it can also create new ecological burdens if implemented without adequate environmental goals, indicators, and governance [1], [2], [3], [4].

In terms of opportunities, Industry 4.0 technology allows companies to obtain real-time operational data, improve process precision, perform predictive maintenance, and optimize the use of raw materials, energy, water, and machine capacity. Sensors and IoT can detect leaks, waste, or quality deviations early; data analytics and artificial intelligence can help choose more efficient production scenarios; Meanwhile, digital twins and cyber-physical systems can be used to simulate environmental impacts before process changes are physically implemented. This mechanism has the potential to reduce waste, emissions, production defects, resource consumption, and operational costs simultaneously. However, the benefits of sustainability do not arise automatically from the adoption of technology, as the contribution of each technology differs according to the character of the industry, the scale of the company, the readiness of the organization, the source of energy, and the quality of data integration in the decision-making process [3], [5], [6].

On the other hand, the expansion of digital infrastructure has direct and indirect environmental consequences. The production, operation, and disposal of digital devices requires large amounts of energy, critical minerals, water, and materials; Data centers, communication networks, sensors, and computing devices also add to the need for electricity and generate electronic waste. Efficiencies achieved through automation can also trigger a rebound effect, namely reduced costs and increased production capacity, which ultimately increases total production, energy consumption, and resource utilization. Analysis at the economic level shows that digitalization can indeed improve energy efficiency and drive changes in production structures, but the growth of the technology sector, device consumption, and the expansion of economic activity can offset and even exceed those savings. Therefore, the evaluation of Industry 4.0 needs to include life-cycle impacts and systemic impacts, not just efficiency on a single machine or one stage of production [2], [3], [4], [7].

The linkage of Industry 4.0 with the circular economy expands environmental mitigation opportunities as digital data can support material tracking, product life extension, maintenance, reuse, remanufacturing, and recycling. IoT technologies, blockchain, and digital platforms can improve the transparency of material flows and facilitate coordination between producers, suppliers, consumers, collectors, and waste processors. However, research evidence shows that new digital technologies produce stronger circular outcomes when accompanied by supply chain integration, product design that can be repaired and dismantled, data interoperability standards, and business models that provide incentives to maintain material value for as long as possible. Thus, digitalization should be placed as a means to achieve environmental and circularity goals, not as an end goal measured only by the number of devices, connectivity, or level of automation [8], [9], [10].

Recent empirical findings also show that the influence of digital transformation on environmental performance is heterogeneous. A number of studies have found that digitalization can improve environmental performance through green innovation, increased human capital, environmental information disclosure, resource allocation efficiency, and governance strengthening. However, the magnitude of these influences varies according to ownership, company size, pollution intensity, technology level, competitive pressure, and strictness of environmental regulations. In fact, the relationship between digital transformation and environmental performance can be nonlinear because in the early stages companies must bear energy consumption, device investment, and organizational adjustments before efficiency benefits and pollution reduction are realized. This heterogeneity emphasizes the need for a contextual, gradual, and action-based mitigation strategy, not the assumption that all forms of digitalization are always synonymous with industrial greening [11], [12], [13].

The urgency of this discussion is even greater for developing countries, including Indonesia, which face the simultaneous need to increase industrial productivity, expand competitiveness, create quality jobs, and meet environmental commitments. Companies in developing countries, especially small and medium-sized enterprises, often face limitations in financing, digital infrastructure, data quality, workforce competence, access to clean technology, and regulatory uncertainty. Without institutional support, Industry 4.0 risks widening the gap between large and small companies, shifting the environmental burden to regions with weak oversight, or reinforcing dependence on fossil energy and short-lived imported devices. Instead, a combination of green investment incentives, skills development, standardization, supply chain partnerships, and performance-based regulation can help companies leverage digital technologies to achieve more inclusive resource efficiency and sustainability [14], [15], [16].

Although the literature on Industry 4.0 and sustainability is growing rapidly, studies are still often fragmented between research groups that emphasize the benefits of efficiency and innovation and those that highlight energy consumption, e-waste, rebound effects, and institutional gaps. Many studies also focus on specific technologies or company performance separately, so they have not always linked positive and negative impacts to mitigation strategy packages that include technology design, circular economy, renewable energy, environmental management, organizational capacity building, and public policy. This article departs from this gap by placing Industry 4.0 as a sociotechnical system in which the environmental consequences are determined by the choice of technology, energy sources, process design, organizational behavior, business models, regulations, and interactions between actors in the value chain [2], [3], [4], [17].

Based on these backgrounds and gaps, this article asks two research questions. First, what are the positive and negative implications of the application of Industry 4.0 on the environment, especially in the aspects of resource efficiency, energy consumption, emissions, waste, and product lifecycle management? Second, what mitigation strategies need to be implemented by companies, governments, and other stakeholders so that the transformation of Industry 4.0 results in increased productivity while reducing environmental impact in a real and sustainable manner? The question was formulated to avoid a deterministic approach that assumes that digital technology is always environmentally friendly, while also to identify the conditions that make digitalization truly support the green transition [2], [5], [7].

In line with the research question, the purpose of this article is to conceptually and critically analyze the relationship between Industry 4.0 and the environment; mapping the ecological opportunities and risks arising from the application of digital technology in the industry; and develop mitigation strategies that integrate energy and resource efficiency, circular economy, green innovation, e-waste management, renewable energy use, environmental performance measurement, and collaborative governance. The contribution of the article lies in the unification of technological, management, ecology, and policy perspectives so that the resulting strategies do not stop at the adoption of the device, but direct industrial transformation to measurable, equitable, and appropriate environmental outcomes in the context of developing countries [3], [10], [15].

To achieve this goal, the discussion of articles is arranged in order. After the Introduction, the Literature Review section explains the conceptual and theoretical foundations regarding environmental science, Industry 4.0, sustainability, and the relationship between digitalization and ecological impact. The Methodology section explains the literature review approach used to select, read critically, and synthesize literature. The Results and Discussion section then outlines the environmental impact of Industry 4.0 and its mitigation strategies, followed by a synthesis that explicitly answers the research questions. The Conclusions section summarizes key findings, policy and managerial implications, limitations, and further research agenda.

LITERATURE RIVIEW

1. Environmental Science, Sustainability, and Ecological Boundaries

Environmental science is a multidisciplinary field that integrates ecology, earth sciences, chemistry, environmental health, economics, public policy, and social sciences to explain the reciprocal relationship between human systems and natural systems. The object of the study does not stop at pollution as the final output of economic activities, but includes energy and material flows, land use changes, ecosystem carrying capacity, risk distribution, and the capacity of communities and institutions to prevent or restore damage. This perspective places industrial activities as part of a socio-ecological system: increased productivity can create well-being, but raw material extraction, energy consumption, emissions, and waste can reduce the resilience of ecosystems if not managed throughout the product life cycle. The update of the planetary boundaries framework shows that six of the nine limits of the Earth system's processes have been exceeded, so industrial innovations need to be judged on their ability to reduce absolute pressures on climate, biosphere, freshwater, land use, and new entities, not just on relative economic efficiency [18].

In the context of this article, environmental sustainability is understood as the ability of production systems to meet economic and social needs by maintaining resource stocks, ecosystem functions, and environmental quality between generations. This concept demands a distinction between eco-efficiency and eco-effectiveness. Eco-efficiency is oriented towards reducing energy, materials, emissions, or waste per unit of output, while eco-effectiveness assesses whether the technology design and overall production model actually reduce ecological stress, extend product life, maintain materials in the utilization cycle, and prevent the transfer of environmental burdens to other sites or stages. Therefore, Industry 4.0 impact measurement should include intensity indicators and absolute indicators, clear system boundaries, and lifecycle perspectives so that efficiency improvements in factories do not mask increased energy consumption, critical materials, or waste on digital infrastructure [2], [17].

2. Industry 4.0 as a Sociotechnical Transformation

Industry 4.0 refers to the integration of cyber-physical systems, industrial Internet of Things, cloud and edge computing, big data analytics, artificial intelligence, robotics, simulation, additive manufacturing, digital twins, and supply chain connectivity to form intelligent, connected, adaptive, and data-based production processes. Different from conventional automation that primarily replaces manual work on a single machine or a single line, Industry 4.0 connects physical assets, software, humans, and external partners so that decisions can be made in real-time and across organizational boundaries. These technologies do not have uniform sustainability consequences; Its contribution depends on the use function, energy source, scale of deployment, process design, and sector context. Therefore, technology assessments must be carried out specifically, because technologies that are very beneficial for efficiency in one industry can have different energy or material footprints in another industry [1], [5].

The sociotechnical view emphasizes that Industry 4.0 is not a collection of devices that work neutrally, but rather technological configurations, organizational structures, worker competencies, management practices, data standards, supplier relations, and institutional rules. Environmental benefits don't appear automatically after a company buys sensors, robots, or analytics software. Data must be converted into operational decisions, environmental targets must be integrated into performance indicators, and workers need to have the ability to interpret information and make improvements. Critical studies also show that the Industry 4.0 narrative often emphasizes productivity and growth more strongly than evidence of reducing environmental impact. Thus, sustainability must be included from the transformation planning and design stages, rather than being treated as an additional benefit after digitalization has taken place [2], [19].

3. The Conceptual Relationship of Industry 4.0 and Environmental Performance

Conceptually, the influence of Industry 4.0 on the environment takes place through three layers. The first layer is the direct impact of digital technology, including energy for computing and communication, hardware needs, water use for cooling, mineral extraction, and electronic waste. The second layer is the possible impact, i.e. changes to physical processes that occur due to sensors, analytics, automation, and connectivity, such as defect reduction, predictive maintenance, energy optimization, or increased asset utilization. The third layer is systemic impact, namely changes in production volumes, consumption patterns, value chain configurations, and business models. This layered framework explains why energy-saving technologies at the machine level can still increase total impact when driving output expansion, faster device changeover, or new consumption [7], [20].

The relationship can also be explained through input–process–output–outcome logic. Industry 4.0 Technology functions as an input for digital capabilities; The mediation process occurs through sustainable operating practices, supply chain integration, data-driven decision-making, green innovation, and the circular economy; its direct output can be a decrease in energy intensity, materials, downtime, defects, and waste; Meanwhile, the final outcome is changes in emissions, environmental quality, resource resilience, and sustainable performance. Empirical research shows that sustainable operating practices can be an important mediator between Industry 4.0 technology and sustainable performance. These findings reinforce the argument that technology is an enabler, while environmental outcomes are determined by organizational processes that transform digital information into corrective actions and innovations [4], [6], [21].

4. Theoretical Perspectives to Explain Environmental Mitigation

a. Natural-Resource-Based View and Dynamic Capabilities

Natural-resource-based view (NRBV) views pollution prevention, lifecycle product management, and sustainable development as strategic capabilities that can generate excellence when embedded in the company's resources and routines. Within this framework, Industry 4.0 data and technologies have environmental value when they strengthen companies' ability to identify waste, trace sources of emissions, control risks, design products that are easier to repair or recycle, and collaborate with suppliers. Evidence on Vietnamese manufacturing companies shows that digital transformation improves environmental performance through data-driven ethical decision-making, and the influence is stronger when organizations have mindfulness or awareness of the consequences of decisions. That is, the quality of governance and environmental orientation determine whether data is used only for productivity or also to prevent externalities [21], [22].

Dynamic capability theory complements NRBV by emphasizing sensing, seizing, and reconfiguring capabilities. Companies need to detect regulatory changes and environmental risks, seize green technology opportunities, and then reconfigure assets, processes, competencies, and supply chain relationships. The combination of environmental assets, Industry 4.0 technology, research and development, production flexibility, and human capital management proved to be more meaningful than the adoption of technology separately. However, digital transformation can also exhibit a nonlinear relationship with environmental performance: benefits increase to a certain degree, then decrease when complexity, overinvestment, consumption of digital resources, and organizational inertia exceed the company's ability to manage them. This perspective prevents the assumption that more digitalization always results in a better environment [23], [24].

b. Technology–Organization–Environment, Institutional Theory, and Stakeholders

Framework *Technology–Organization–Environment (TOE)* explained that the adoption of Industry 4.0 is simultaneously influenced by technological characteristics, organizational readiness, and the external environment. The technology dimension includes compatibility, complexity, interoperability, data security, and perceived benefits. The organizational dimension includes financial resources, digital competencies, leadership, culture, measurement systems, and the ability to change. The environmental dimension includes regulation, customer pressure, competition, infrastructure support, access to financing, and supplier readiness. The integration of sustainability goals into these three dimensions is important so that investment decisions assess not only productivity, but also energy consumption, device lifespan, material circularity, and socio-ecological consequences [16], [21].

Institutional theory and stakeholder theory explain why organizations adopt green practices when facing regulatory, normative, and market pressures. Governments can form incentives through emission standards, carbon taxes, extended producer responsibility, green procurement, data disclosure, and technology support for small businesses. Customers, investors, workers, communities, and supply chain partners also influence company priorities through demands for transparency and accountability. In emerging economies, external pressures must be balanced with capacity building because limited capital, skills, digital infrastructure, and access to technology can make good standards difficult to implement. The literature shows that a lack of resources and competencies is a fundamental obstacle to Industry 4.0 integration and sustainability in small and medium-sized enterprises [14], [15], [16].

5. Positive Mechanisms for the Environment

a. Energy, Material and Process Efficiency

The first positive mechanism is increased visibility and control of the process. IoT sensors can measure energy, water, materials, temperature, pressure, and emissions consumption at previously unmonitored points. Analytics and artificial intelligence then identify waste patterns, optimize machine schedules, adjust process parameters, and support rapid responses to deviations. Predictive maintenance reduces sudden breakdowns, defective products, material loss, and premature component replacement. Digital twins and simulations allow for virtual testing of process changes before implementation, so the risk of physical experiments and wastage can be reduced. However, the magnitude of the benefits still depends on data quality, system integration, and the ability of companies to set environmental indicators as an objective function, not just cost and speed [3], [5], [17].

Additive manufacturing and flexible production has the potential to reduce material use by producing components according to geometry and required quantities, reducing inventory, and supporting the production of parts to extend asset life. Robotics and machine vision can improve precision so that scrap and rework decrease. However, those gains must be tested through a life-cycle approach because special materials, electricity consumption, post-processing stages, and production scale can change outcomes. Therefore, the selection of technology should use a comparison of scenarios that include energy sources, material intensity, utilization rates, lifespan, and end-of-life of the device so that green claims do not only come from one stage of production [2], [5].

b. Environmental Monitoring and Decision Making

Big data, remote sensing, AI, and sensor networks expand the capacity to monitor air, water, soil, chimney emissions, leaks, and land cover changes. Real-time systems can shorten the gap between contamination occurrence and corrective action, while predictive analytics help prioritize inspections and maintenance. At the enterprise level, the integration of environmental data with production systems allows traceability of the causes of emissions down to machines, batches, raw materials, or suppliers. At the policy level, more granular data can support risk-based enforcement and evaluation of program effectiveness. However, censorship validity, interoperability, data ownership, algorithmic bias, cybersecurity, and possible manipulation of reporting need to be managed in order for digitization to increase accountability, not just generate large volumes of data [13], [22].

6. Risks and Paradoxes of the Digitalization Environment

a. Direct Footprint of Digital Infrastructure and E-Waste

The first risk comes from the physical footprint of the digital ecosystem. Data centers, communication networks, IoT devices, robots, sensors, batteries, and computing devices require electricity, water, metals, critical minerals, plastics, as well as manufacturing processes that produce emissions. Devices that quickly wear out or cannot be repaired add to electronic waste and loss of valuable materials. Because the footprint is often in a different location than the user's plant, the company can look more efficient locally, while the burden shifts to the device manufacturer, power plant, data center, or mineral supplying country. Assessments that only calculate energy consumption at the site of operations will underestimate the upstream and downstream impacts; Therefore, the procurement of devices, modular designs, the right to repair, the extension of life, the use of low-carbon energy, and product return schemes need to be part of the mitigation strategy [7], [17], [20].

b. Rebound Effect and Production Expansion

Increased efficiency can lower the cost per unit and trigger greater utilization, increased output, or the formation of new demand. This phenomenon is known as the rebound effect. In industry, the energy savings of more efficient machines can be partially offset by longer operating hours or capacity expansion. Studies in the manufacturing sector show a partial rebound that reduces energy savings and technically estimated emissions. Digitalization also accelerates product innovation, personalization, logistics, and transactions, so that efficiency gains per unit do not necessarily result in a decrease in absolute impact. Consequently, policies do not rely enough on efficiency; Absolute emission and material targets, environmental prices, renewable energy, design limits, and monitoring of total yields after changes in production scale are required [7], [25].

c. Capacity Gaps and Governance Risks

Inequality of access to technology can result in an unbalanced distribution of benefits and burdens. Large companies typically have the capital, data, expertise, and bargaining position to adopt technology efficiently, while small businesses face start-up costs, uncertainty of benefits, lack of competencies, and legacy systems that are difficult to integrate. In the global value chain, the demands of digital tracking and environmental compliance can increase transparency, but also potentially exclude small suppliers if capacity building support is not available. Other risks include vendor dependency, data concentration, cyberattacks that disrupt environmental facilities, and the use of non-transparent algorithms. Therefore, a just transformation requires open standards, interoperability, affordable financing, training, data protection, and transition policies for groups with limited capacity [14], [16], [26].

7. Industry 4.0, Circular Economy and Value Chains

The circular economy shifts the linear logic of take-make-throw towards waste prevention, reduction of primary material use, maintenance of product value, reuse, repair, refurbishment, remanufacturing, and recycling. Industry 4.0 can support this transition through product passports, condition sensors, material identification, ownership tracking, sharing platforms, predictive maintenance, and backflow analytics. Product condition data allows companies to determine when components are maintained, reused, or remanufactured; material data helps with separation and recovery; Meanwhile, digital platforms facilitate a product-as-a-service model that shifts producer incentives from volume sales to maintenance of functionality and lifespan [8], [9].

Although technology strengthens information, circularity requires coordination between actors. The integration of suppliers, manufacturers, distributors, users, service providers, collectors, and end-of-life processors determines whether information can follow the material along the chain. Research shows that supply chain integration mediates the relationship between Industry 4.0 technology and circular economy practices. In the global value chain, challenges increase due to differences in standards, jurisdictions, infrastructure, responsibilities, and value sharing. Tracking systems should be accompanied by governance that determines data quality, access rights, return financing, product liability, and mechanisms so that small suppliers benefit, not just the cost of compliance [10], [26].

8. Conceptual Synthesis and Article Analysis Framework

Based on the literature, this article views the relationship between Industry 4.0 and the environment as a conditional relationship. Digital technology provides measurement, prediction, coordination, and automation capabilities; These capabilities impact the environment through sustainable operating practices, green innovation, circular economy, and value chain governance. The results are moderated by energy sources, production scale, product design, data quality, human competence, organizational readiness, policies, and the company's position in the value chain. At the same time, the direct footprint of digital devices, rebound effects, and load shifts can reduce or reverse the benefits. This model describes a variety of empirical findings that suggest that digital transformation can improve environmental performance in some organizations, but its effects are heterogeneous, nonlinear, and context-dependent [11], [12], [24].

The analysis framework produces four evaluation principles. First, additionality: whether technology produces improvements that do not occur without intervention. Second, life-cycle integrity: whether the benefits remain positive after the upstream, operational, and end-of-life impacts are calculated. Third, absolute decoupling: whether total emissions and resource use decrease despite increasing economic output. Fourth, just transition: whether benefits, costs, data, and capacity are shared fairly. These four principles are the link between the Literature Review and the Results and Discussion section. The next analysis needs to assess not only what technologies are available, but also what organizational conditions and policies make them truly reduce environmental impact as well as prevent unwanted side effects [2], [13], [19].

METHODOLOGY

This article uses the qualitative literature review method or qualitative literature review method that is non-systematic, interpretive, and critical. The choice of this method is based on the multidisciplinary nature of the problem: the implications of Industry 4.0 on the environment are not only shaped by the performance of digital devices, but also by energy systems, production design, organizational behavior, value chain configuration, institutional capacity, and public policy. Unlike systematic literature review which requires a standard search protocol, exhaustive scope, a replicable screening process, and formal reporting of the selection flow, this study uses purposive and iterative literature search to find the concepts, mechanisms, differences in findings, and boundary conditions that are most relevant to the research question. The approach is appropriate for integrating fragmented fields of science, testing the assumption that digitalization always improves sustainability, and building conceptual explanations that connect technology, operating practices, ecological impacts, and governance. Even though it does not use the SLR or PRISMA protocols, the study process is still guided by the focus, relevance criteria, transparency of sources, and synthesis goals that have been established from the beginning [27], [28], [29].

The literature search was directed to articles in English and Indonesian scientific journals published mainly since 2020 and discussed Industry 4.0, digital transformation, artificial intelligence, Internet of Things, smart manufacturing, environmental sustainability, energy efficiency, carbon emissions, electronic waste, circular economy, green innovation, sustainable supply chains, and environmental governance. Sources are found through keyword searches and chain searches of reference lists as well as articles citing relevant works on academic search engines, publisher databases, and scientific journal portals. The literature is included when it has a direct relationship with at least one of two study focuses: first, mechanisms that explain the positive and negative impacts of Industry 4.0 on energy use, materials, emissions, waste, and product life cycles; Second, mitigation strategies at the company, supply chain, government, or stakeholder level. Priority is given to peer-reviewed articles from reputable journals, articles that provide verifiable DOIs or publisher addresses, empirical studies that explain the mechanisms and conditions of implementation, and conceptual articles that help build an analytical framework. Sources that cannot be verified, are merely technological promotions, repeat the same information, or do not explain their relationship to environmental performance are not the main basis for the argument. The collection of literature proceeds iteratively until the main themes have been repeated and no new substantive categories are found that meaningfully alter the structure of the analysis [27], [28].

Analysis is carried out through repeated reading, analytical record-keeping, concept grouping, and thematic synthesis. Information from each source is mapped according to the type of technology, sector or context, mechanism of influence, environmental indicators, reported benefits, risks or trade-offs, enabling factors, barriers, and responsible actors. The initial code is then compared and combined into themes that include resource efficiency, energy consumption and digital carbon footprint, e-waste, circular economy, value chain integration, organizational capabilities, regulation, and transitional justice. Consistent findings are used to identify general patterns, while different or opposite results are examined to find boundary conditions such as energy mix, production scale, digital readiness, product design, and developing country contexts. The final synthesis is arranged argumentatively to answer the first research question through the mapping of positive-negative implications and answer the second question through the formulation of complementary mitigation strategies. The credibility of the analysis is strengthened by comparing evidence from various disciplines and contexts, checking the existence of DOIs or publisher pages, maintaining negative findings, and maintaining consistency between claims, sources, and conclusions. Since this approach is not SLR, the article does not claim that all available publications have been covered; Its contribution lies in the depth of interpretation, cross-field integration, and development of conceptual synthesis relevant to theory, policy, and practice [29], [30], [31], [32].

RESULT AND DISCUSSION

1. Mapping the Environmental Implications of Industry 4.0

The results of the literature synthesis show that the environmental implications of Industry 4.0 cannot be simply categorized as positive or negative. The impact is formed through the interaction between technological functions, changes in the production process, energy mix, output volume, device lifespan, business model, and governance quality. At the operational level, sensors, the Internet of Things (IoT), artificial intelligence, data analytics, robotics, and cyber-physical systems expand the company's ability to measure energy and material flows in real-time. This information can be used to reduce process variations, product defects, downtime, raw material consumption, and unproductive energy use. However, field studies show that companies often find it easier to recognize economic and productivity benefits than environmental benefits, so sustainability goals need to be explicitly set from the design stage of a digitalization program [33], [34], [35].

The mechanism of environmental benefits most emerges when digital technology is linked to sustainable operating practices. Predictive maintenance, for example, not only reduces the cost of damage, but also extends the life of the asset, avoids the production of defects, and reduces the need for replacement components. Data-driven process control can identify deviations before producing products that need to be discarded, while more precise production planning can reduce overinventory and energy consumption when machines are idle. Thus, the environmental value of technology does not lie in its devices, but rather in the organization's capacity to translate data into pollution prevention decisions, resource efficiency, and process innovation [6], [21], [23].

On the other hand, an increase in relative efficiency does not necessarily result in an absolute decrease in environmental pressure. Automation can lower energy per unit, but lower production costs and capacity flexibility can drive increased production volumes. The rebound effect is important because the benefits at the machine level can be offset by output expansion, increased frequency of product replacements, or new demand facilitated by digital platforms. Therefore, performance evaluations must compare intensity indicators—such as energy per unit—with absolute indicators—such as total energy, emissions, materials, and waste—over the same period [7], [25].

2. Resource Efficiency, Emissions, and Digital Ecological Footprint

The first positive implication answers the industry's need to separate production growth from resource use growth. Industry 4.0 technology supports process visibility, scheduling optimization, defect reduction, automatic quality control, and dynamic adjustment of machine parameters. In this context, companies can build energy and material baselines, recognize waste points, and test improvement scenarios before making physical investments. Cross-border evidence also shows that the potential for decarbonization and dematerialization differs by sector, company size, level of digitalization, and maturity of environmental management systems; Therefore, technology packages need to be chosen based on dominant sources of impact, not on adoption trends [1], [5], [19].

The negative implications come from the life cycle of digital technology itself. Sensor devices, servers, communication networks, data storage, and cooling systems require electricity, water, metals, semiconductors, and physical infrastructure. Moving computing to a cloud provider can also shift emissions from a company's direct inventory to value chain emissions, making carbon footprint transparency more difficult if service providers don't provide adequate data. Therefore, the procurement of digital services needs to include requirements for energy openness, electricity mix, data center efficiency, processing locations, and hardware lifecycle emissions [33], [36].

The growth of artificial intelligence adds to the need to distinguish high-value uses of the environment from disproportionate uses of computing. AI can improve energy demand forecasting, renewable energy integration, asset maintenance, and grid optimization; But those benefits must be compared to the computing energy, device needs, and data quality used. The mitigation principle is to choose the right model and architecture—not always the largest—using efficient, low-carbon data centers, avoiding purposeless data collection, and incorporating carbon and energy budgets into digital project governance [3], [37]. Ecologically, the company's target is not enough just to reduce greenhouse gas emissions. Pressures on water, biodiversity, land-use change, and critical materials also need to be taken into account, especially in the supply chain of electronic devices and energy. The perspective of planetary boundaries reminds us that innovations that lower carbon but magnify the extraction of toxic materials or waste can move problems from one dimension of the environment to another. Therefore, life cycle assessments, material flow analysis, and multidimensional indicators need to complement carbon measurements [17], [18].

3. Circular Economy and Product Lifecycle Management

The circular economy is the main path to transforming digital capabilities into material stress reduction. IoT can provide information regarding product condition, location, use, and maintenance needs; Blockchain or ledger systems can help trace the origin of materials; data analytics can improve reverse flow prediction; and Digital Product Passport can connect design, composition, repair, disassembly, and recycling information. However, technology is only effective if the product is designed to be durable, repairable, modular, and easy to disassemble. Without design changes and economic incentives for product returns, digital data only increases transparency without closing the material cycle [8], [38], [39].

Studies on the relationship between Industry 4.0 and the circular economy show that reduction, reuse, recovery, remanufacturing, and recycling require a combination of technology, supply chain integration, and business models. Additive manufacturing can reduce residual materials in certain applications and provide spare parts on demand, but the benefits depend on the type of material, process energy, machine utilization rate, and the ability to recycle the powder or supporting materials. Robotics and computer vision can improve sorting, while digital platforms can connect waste owners, collectors, and users of secondary materials. Therefore, companies need to assess benefits at the system level, rather than generalizing one technology to the entire circular strategy [9], [10], [40].

Indonesia's experience provides evidence that digital platforms can strengthen the collection, sale, and recovery of materials through a network of waste banks and recyclers. The strategic value is not only automation, but also the reduction of information costs, the expansion of the secondary material market, and the increase of traceability. However, the digitalization of waste management needs to take into account device access, digital literacy, data quality, the role of the informal sector, and the sustainability of revenue models. Interventions that simply create applications without ensuring the demand for recycled materials, reverse logistics, and collection institutions will be difficult to sustain [26], [41].

At the value chain level, data integration between actors is an important requirement. Manufacturers need usage and damage data, service providers need manual access to repairs and spare parts, while final processors need material and hazardous materials information. Interoperability, data ownership governance, cybersecurity, and benefit-sharing standards must be agreed so that small suppliers do not just become data providers without gaining economic value. As such, the digital circular economy requires an institutional architecture that supports secure, proportional, and usable data exchange across organizations [26], [39].

4. Smart Manufacturing, Digital Twin, and Energy Transition

Smart manufacturing provide mitigation opportunities through the integration of measurement, simulation, prediction, and control. Digital twins allow companies to create virtual representations of machines, lines, products, or factories to analyze energy and material consumption before changes are applied to physical systems. In energy-intensive industries, the merging of digital twins and big data can support real-time control, maintenance planning, lifecycle analysis, and identification of savings opportunities. However, digital twins must be built from clear operational questions; Models that are complex but not connected to decisions, data quality, or implementation responsibilities will result in computational costs without environmental improvements [42], [43].

The integration of renewable energy is also becoming more feasible when digital systems are able to adapt production to energy availability, price, storage capacity, and process limits. AI can help forecast solar or wind generation, storage optimization, demand response, and industrial load scheduling. However, energy savings must be placed after the principle of hierarchy: avoiding unnecessary needs, improving process efficiency, recovering heat or energy, then replacing fossil sources with renewable energy. If digitization only optimizes wasteful systems without changing the process design, the long-term benefits will be limited [37], [42].

Energy strategies need to distinguish between rapid action and structural transformation. Quick actions include sub-metering, leak detection, operation timing, compressed air optimization, and predictive maintenance. Structural transformation includes process electrification, product redesign, renewable energy integration, storage, and plant configuration changes. Digital technology functions to connect the two levels through data, simulation, and performance verification. Investment priorities should be determined based on the cost of emission reductions, potential absolute savings, technical readiness, and operational risk, rather than solely the level of technological sophistication [3], [12].

5. E-Waste and Liability Along the Value Chain

E-waste is the most obvious paradox of digital transformation. Sensors, industrial computers, communication devices, batteries, and control components accelerate digitalization, but short service life, limited repairs, and device replacement can increase the flow of waste containing valuable and hazardous materials. The mitigation approach needs to shift from final management to circular design: extending the life of the device, providing parts and software updates, facilitating disassembly, using modular components, and developing a retrieval system [44], [45].

Extended Producer Responsibility (EPR) It needs to be strengthened with data that allows regulators and the public to assess the number of devices being marketed, collected, reused, repaired, and recycled. However, Digital Traceability is not a substitute for enforcement. Research on e-waste systems shows that fragmented rules, weak economic incentives, conflicts between actors, and technological limitations can form lock-ins that perpetuate low-value practices. Therefore, EPRs need to set targets that differentiate the reuse, remanufacturing, and recycling of materials; preventing the export of environmental burdens; and integrating informal actors through safety standards, training, access to financing, and formal partnerships [45], [46].

The behavior of the organization's consumers and users also determines success. Devices that are stored, disposed of with mixed waste, or replaced before the end of technical life reduce the chances of circularity. Companies can implement procurement policies that require repairability, long-term software support, energy efficiency, recycled material content, and schematics take-back. At the same time, secure data deletion and privacy guarantees are required so that the device can be returned or reused without information risk [33], [44].

6. Regulations, Governance, and Incentives for Green Innovation

Environmental regulation is needed to turn the potential benefits of digitalization into accountable outcomes. Empirical evidence suggests that stricter regulation can boost green investment and innovation, but its influence is influenced by instrument design, enforcement capacity, market conditions, and company capabilities. Emissions standards, reporting obligations, carbon pricing, efficiency requirements, and producer responsibilities should be designed to complement each other. Results-based regulation leaves room for innovation, while minimum standards prevent companies from profiting from non-compliance [47], [48], [49].

The relationship between regulation and innovation is not always linear. A disproportionate burden of compliance can divert resources away from innovation, especially in small companies, while overly weak regulation does not change investment decisions. Policies need to provide long-term certainty, implementation stages, technical assistance, and differentiation based on environmental risks. A combination of supervision, transparency, investment incentives, and market mechanisms can encourage companies to change innovation intentions into real innovation behaviors [50], [51].

Digital transformation also expands governance capabilities through emissions monitoring, data audits, information disclosure, and risk analysis. However, a lot of environmental data is not synonymous with accountability if the definition of indicators, organizational boundaries, emission factors, and verification methods is inconsistent. Companies need to integrate digital systems with environmental management systems, internal controls, audits, and board oversight. Improved ESG performance and green innovation are more likely to occur when digitalization reduces information and financing constraints, rather than when used only for sustainability communication [22], [52], [53].

For the government, policy strategies need to strengthen public data infrastructure and interoperability. Emissions registries, energy data, licensing, waste management, and corporate reporting can be gradually linked with privacy and security protections. The data enables risk-based surveillance, non-compliance identification, assessment of incentive effectiveness, and low-carbon industrial estate planning. However, surveillance algorithms should be transparent and not replace field inspections, especially when the quality of company data is uneven [12], [13].

7. Organizational Readiness, SMEs, and Developing Countries Context

Limited capital, competencies, data, and infrastructure make small and medium-sized companies at risk of being left behind in the green-digital transformation. Evidence in SMEs shows that top management commitment and technology infrastructure readiness are important factors, while supply chain integration is not automatically effective if the relationship between actors, standards, and benefits is unclear. Therefore, the adoption program must start from a high-value environmental problem and proportionate technology, not from a large investment that does not yet have a business case [16], [54].

A phased approach can start with basic measurement, digitization of utility data, maintenance, quality control, and waste tracking. Once the data is stable and competencies improve, companies can move on to predictive analytics, supplier integration, digital twins, or advanced automation. Governments and large corporations can provide shared service centers, testbeds, training, green financing, data standards, and consulting support. The shared model reduces fixed costs, accelerates learning, and prevents SMBs' reliance on a single vendor [14], [15].

In the context of developing countries, strategies must also pay attention to transitional justice. Automation can change the needs of skills and job distribution, while digital formalities can exclude small suppliers or informal workers. Sustainable environmental mitigation needs to be accompanied by reskilling, worker protection, technology access, community participation, and benefit-sharing mechanisms. Thus, success is measured not only by reduced emissions, but also by transformative capabilities to improve the quality of work, competitiveness of local suppliers, and people's access to a healthier environment [3], [54].

8. Integrated Mitigation Strategy Framework

Based on the synthesis, mitigation strategies need to be built in eight consecutive but interconnected pillars. The first pillar is a materiality assessment to identify the sources of the greatest impact on energy, emissions, water, materials, waste, and biodiversity. The second pillar is the baseline and measurement system that combines intensity and absolute indicators. The third pillar is the selection of technologies based on measurable mitigation functions. The fourth pillar is circular process and product design. The fifth pillar is renewable energy and the reduction of digital footprint. The sixth pillar is organizational capabilities, skills, and data governance. The seventh pillar is the integration of the value chain and producer responsibility. The eighth pillar is regulation, incentives, transparency, and independent verification [2], [3], [39].
The sequence prevents technological solutions from looking for problems. The company first establishes priority impacts and absolute targets; Next, select technologies that are able to influence targets, define process owners, and test solutions on a limited scale. Test results should be compared to baseline and include direct technological impacts, process changes, as well as systemic effects. Solutions are only extended when net benefits can be verified and rebound risks, data security, vendor dependencies, and device switchover have been managed [5], [33].

This framework also demands a division of roles. The company is responsible for design, operations, procurement, data, and reporting; technology suppliers are responsible for the efficiency, interoperability, longevity support, and transparency of the device; the government provides regulations, infrastructure, standards, and incentives; financing institutions link capital with environmental outcomes; universities support competency development and evaluation; Meanwhile, the public and consumers exert market pressure and participate in product returns. Such collaboration is necessary because no one actor has all the data and resources to manage impacts throughout the lifecycle (Awan et al., 2022)[14].

Table 1 summarizes the relationship between opportunities, risks, indicators, and mitigation priorities that need to be used to assess the transformation of Industry 4.0 in a balanced manner.

Table 1. Industrial Environmental Mitigation Implications Matrix and Strategy 4.0

Dimensions	Key Opportunities	Key Risks	Mitigation Priorities and Indicators
Energy and Emissions	Process optimization, predictive maintenance, demand response, renewable energy integration.	Computing energy, data centers, rebound effects, absolute production increases.	Baseline; absolute and per unit energy and emissions; energy mix; Carbon Budget of Digital Projects.
Materials and Waste	Defect reduction, material tracking, remanufacturing, sorting and secondary materials markets.	Extraction of minerals, short-lived devices, e-waste and hazardous materials.	Modular design; repairability; take-back; The rate of reuse, remanufacturing, and recycling is high-value.
Water and Ecosystems	Sensors for leaks, water quality control, real-time environmental monitoring.	Water consumption for processing and cooling; transfer of loads to other suppliers or regions.	Water balance; effluent quality; location and season; life cycle assessment and biodiversity risk.
Data and Governance	Traceability, auditing, risk-based supervision, value chain transparency.	Bad data, digital greenwashing, cybersecurity, access inequality and vendor dependency.	Data standards; verification; access control; interoperability; Algorithm audit and methodological transparency.
Organization and Workforce	Quick decision-making, learning, safety, value-added work.	Competency gaps, resistance, exclusion of SMEs and informal workers.	Training; worker participation; gradual adoption; shared services; indicators of work quality and supplier inclusion.
Policy and Markets	Green innovation, financing, compliance, internalization of environmental costs.	Fragmented regulations, disproportionate burdens, pollution relocation, misguided incentives.	A combination of standards, pricing, incentives, EPR, green procurement, policy enforcement and evaluation.

Source: Author's Synthesis Based On The Literature Studied.

9. Synthesis and Answers to Research Questions

The answer to the first research question is that Industry 4.0 has dual and conditional environmental implications. Positive impacts emerge through energy and material efficiency, defect and waste reduction, predictive maintenance, logistics optimization, pollution monitoring, support for renewable energy, and increased traceability for the circular economy. Negative impacts arise through electricity and water consumption of digital infrastructure, emissions hidden in cloud services, extraction of critical materials, electronic waste, security and data quality risks, and rebound effects that increase production or absolute consumption. Thus, digital technology can only be considered environmentally friendly if its net benefits are proven at the limits of the system and an adequate time horizon [2], [7], [33].

Another important finding is that the relationship between digitalization and environmental performance is mediated by organizational practices. The same technology can produce different outcomes due to differences in energy mix, worker competencies, management systems, supplier integration, product design, regulations, and financing capacity. Empirical evidence regarding corporate heterogeneity and nonlinear relationships reinforces the conclusion that more adoption is not always better. The strategy should be directed at the adequacy of technology, the quality of implementation, and the achievement of absolute environmental targets [11], [12], [24].

The answer to the second research question is that an effective mitigation strategy must combine technical, managerial, circular, energy, and institutional actions. At the enterprise level, the priorities are materiality assessment, baseline, absolute targets, eco-design, process efficiency, low-carbon energy, procurement of repairable devices, data governance, and verification. At the value chain level, the priorities are interoperability, reverse logistics, EPR, data and benefit sharing, and secondary materials market development. At the government level, the priorities are a combination of outcome-based regulations and minimum standards, investment incentives, carbon pricing, SME support, digital-environmental infrastructure, and consistent enforcement [14], [15], [47].

For Indonesia and developing countries, the most realistic path is a gradual and inclusive transformation. The program starts with rapid measurement and improvement that provides economic-environmental benefits, followed by data integration, analytics, and circular innovation. Shared service centers, testbeds, green financing, training, and large enterprise–SME partnerships can reduce cost and knowledge barriers. The informal sector in waste management needs to be seen as a transition partner whose safety, productivity, and market access must be strengthened, not simply replaced by technology [16], [41].

This synthesis emphasizes that the goal of transformation is not to digitize as much as possible, but to reduce measurable environmental impact while maintaining productivity and justice. Investment decisions need to use the avoid–reduce–circularize–decarbonize–verify principle: avoid unnecessary needs, reduce consumption, keep materials in cycles, replace energy and high-emission technologies, and then verify results. This principle bridges environmental goals with Industry 4.0 strategies and prevents digitalization from turning into a new source of ecological burden [3], [17], [55].

CONCLUSIONS AND RECOMMENDATIONS

This article concludes that Industry 4.0 is not an automated environmental solution, but rather a set of digital capabilities that can improve or worsen ecological performance depending on how the technology is designed, used, and regulated. Sensors, IoT, AI, data analytics, robotics, and digital twins can lower waste, increase efficiency, support maintenance, integrate renewable energy, and strengthen material traceability. At the same time, digital infrastructure requires energy, water, minerals, and hardware; generating electronic waste; can hide emissions in the service chain; and potentially trigger a rebound effect. Therefore, the assessment should include the direct impact of technology, the impact of enabling on the process, and the systemic impact on production volumes and consumption.

A solid mitigation strategy needs to start from the identification of material impacts and an auditable baseline. The company then sets absolute targets and intensities, selects technology according to the source of the problem, integrates data with sustainable operating practices, and monitors net benefits throughout the lifecycle. The circular economy must be implemented through durable and repairable design, reuse, remanufacturing, reverse logistics, manufacturer responsibility, and secondary materials markets. Process efficiency needs to continue with energy decarbonization, while digital projects need to have energy, carbon, device, and lifespan budgets.

At the organizational level, success is determined by leadership, competence, culture of improvement, data governance, and the integration of environmental goals into investment decisions. Technology needs to be linked to performance indicators, implementing responsibilities, verification mechanisms, and board supervision. SMEs need a phased pathway, shared services, training, testbeds, interoperability standards, and financing that links payments or incentives to environmental outcomes. This approach is more realistic than driving the purchase of advanced technology without process readiness and human resources.

At the policy level, governments need to incorporate minimum standards, performance-based regulations, carbon pricing or markets, innovation incentives, green procurement, Extended Producer Responsibility, and information disclosure. Digital data can strengthen surveillance and evaluation, but it still requires consistent indicator definitions, security, audits, and field inspections. In the Indonesian context, policies must also integrate small suppliers, waste banks, collectors, and informal actors so that the benefits of the circular economy and digital transformation are not concentrated in large companies.

This study has limitations because it uses a qualitative literature review that is not intended to cover all publications or produce estimates of combined effects. Subsequent research needs to test mitigation frameworks through longitudinal and cross-sectoral studies, compare pre- and post-adoption impacts, and measure emissions, energy, water, materials, and waste in absolute terms.

Other agendas include AI and digital twin lifecycle assessments, the effectiveness of digital product passports and EPRs, the effects of rebounds at the corporate and economic levels, green financing models for SMEs, as well as the distributional impact on workers, small suppliers, and the informal sector. The development of open datasets and replicable verification methods will be critical for green Industry 4.0 claims to be tested transparently.

FURTHER STUDY

This study still has some limitations, so further research on the topic of Industry 4.0 and the Environment: A Review of Ecological Implications and Integrated Mitigation Strategies is needed to make this research more complete and to provide more insights for the author and readers

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