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Review

Linking the Industrial Revolutions and Environmental Impacts: A Review of Global Trends, Strategies, and Future Recommendations

Hadiqa Ahmad, Muhammad Yaqub* and Seung Hwan Lee*

School of Civil and Environmental Engineering, Kumoh National Institute of Technology, 1 Yangho–dong, Gumi, Gyeongbuk 730-701, Republic of Korea.

*Corresponding author Email: dlee@kumoh.ac.kr, yaqub92@kumoh.ac.kr

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Abstract

The Industrial Revolutions (IRs) have dramatically reshaped the industrial landscape by introducing automated production and technological advancements. While these revolutions have driven substantial socioeconomic changes in society, organizations, and government relationships, they have also had significant environmental impacts. These include air, water, and soil pollution, habitat loss, deforestation, resource depletion, food insecurity, and water scarcity. Despite these challenges, IRs hold potential for mitigating environmental damage, such as reducing carbon emissions, soil and water contamination, and resource consumption. Moreover, developing sensors and networks can offer critical insights into environmental changes, aiding the implementation of adaptation and mitigation strategies. This comprehensive review provides a state-of-the-art evaluation of IRs and their environmental interactions, proposing strategies for future environmental policies. It is a valuable resource for future studies and proposals on the digital transformation associated with IRs and their environmental impacts.

Keywords: Energy transition, Artificial intelligence, Industrial revolution, Environmental impacts

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Introduction

Observing industrial revolutions (IRs) is advantageous because they can contribute to socioeconomic and environmental development and provide a foundation for the growth of modern society [1]. The history of IRs highlighting the different technological advancements from the first industrial revolution (1-IR) to the fourth industrial revolution (4-IR) is shown in Fig. 1 [2, 3]. This advancement made industries commonplace by bringing more people to cities, resulting in social, economic, and environmental upheavals. Currently, 4-IR, based on the Internet of Things (IoT) technology to connect devices, such as sensors, robots, and networks to collect big data, is in progress [4 - 6]. Digital applications such as weather forecasting, climate control in intelligent buildings, and self-driving cars are based on data collection [7].

IRs offer numerous benefits, including increased production, improved quality of life, new market opportunities, and reduced barriers to entrepreneurship. However, they are also associated with issues such as inequality, cybersecurity risks, disruptions in core industries, and ethical and environmental problems [8]. Rapid industrial growth has resulted in the discharge of various chemicals into the air, water, and soil, leading to severe environmental impacts [9, 10].

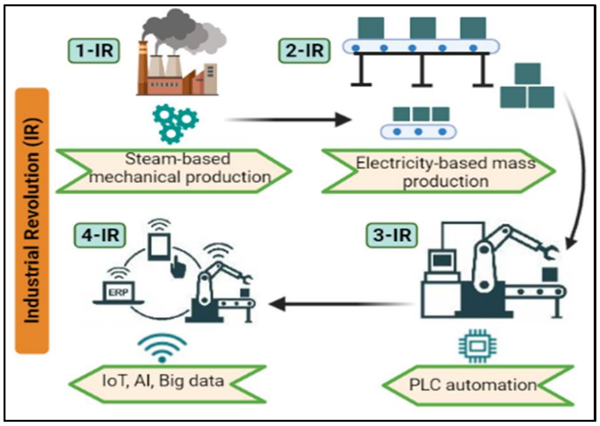

Figure 1. **History of industrial revolutions from 1 to 4-IRs**

This emergence has challenged humanity since the early years of the 21st century. It has prompted the adoption of Agenda 2030, which includes the seventeen Sustainable Development Goals (SDGs) that connect socioeconomic and environmental issues. The agenda specifies that all countries must achieve the SDGs by 2030 [11, 12]. However, the existing literature on IRs primarily focuses on the technical perspective [13], with fewer studies on administrative management [14, 15] and social and environmental aspects [16]. Additionally, the literature has largely ignored the challenges faced by the industry in sustaining economic profitability while improving the environment. Therefore, the potential difficulties of IRs can be defined by the triple bottom line, which considers three dimensions: people, planet, and profits [17].

Purpose of Review

The energy and material consumption associated with the IRs has led to increased waste, contributing to water, air, and soil pollution as well as global warming [18, 19]. According to the Intergovernmental Panel on Climate Change, industries are major producers of greenhouse gases (GHGs) [20]. The International Energy Agency reports that the industrial sector is projected to account for over 50% of global energy consumption from 2018 to 2050, with significant increases in non-Organization for Economic Co-operation and Development (non-OECD) countries [21, 22]. Economic development has fueled the growth of the service sector, which in turn has increased energy usage and pollutant emissions [23]. Despite growing investments in addressing environmental issues, there is a need to strengthen the link between IRs and environmental sustainability [24, 25]. Revising strategies and offering tailored recommendations to developing countries to mitigate environmental impacts is crucial.

IRs have the potential to transform negative environmental impacts into positive ones by showcasing improved global trends in urbanization, demographic changes, deindustrialization, advanced businesses, climate change, globalization, and sustainability [26]. These factors drive high production and energy efficiency in industries through innovation, contributing to the economic sustainability of society and governance. Advanced technologies are reported in the literature for developing environmentally friendly products and services [27, 28]. One study highlighted how environmental factors can reveal estimates of carbon emissions, waste production, pollutant discharge, climate change risks, and natural resource conservation [29]. Another study examined the relationship between IRs and air pollution [30]. In contrast, research discussed the concept of a green economy aimed at reducing poverty and ensuring a healthy and safe environment for humans [31].

To fully understand the impacts of IRs on the environment, an interdisciplinary and integrative approach is required to connect IR with all its environmental impacts [5, 32]. This review aims to consolidate existing studies on IRs and their environmental impacts, examining published research from various journals, countries, publishers, focus areas, and categories. It addresses the consequences of IRs, strategies to mitigate these impacts, and future perspectives. As one of the first studies to explore the link between IR and environmental impacts, it highlights the need for further research to fill gaps in the literature. Policymakers can benefit from this study by gaining a deeper understanding of the IR-environment connection, enabling them to make informed decisions and update existing policies accordingly. Based on the collected data, this review offers strategies for future research to develop sustainable policies through theoretical and practical advancements.

Materials and Methods

Literature Searchand Data Collection

We searched and analyzed academic journal articles published from Jan 2011 to May 2022. Observing and analyzing literature presenting a broader range of trends is crucial for insight into the problems and current situation [33]. Academic scientific papers provide new systematic results and offer researchers access to further information in a specific field [34]. A three-step screening process was adopted to select relevant studies. In the first step, articles were searched using keywords on IRs, environmental impacts, positive and negative impacts of IRs, sustainable development, and green industry on the Web of Science (WoS) database toidentify relevant articles published during the last decade. The peer-reviewed papers were sorted out during the second step. In the third step, articles were evaluated based-on, title, abstract, and conclusion. Only the articles written in English and published in refereed journals were included. The articles were analyzed and compared with the literature on the targeted topic to identify research gaps for future work. Each selected article was rated as appropriate or unimportant based on its title and the ability to respond to the research title. This review article was prepared using the Prisma technique [35]. The reported results were combined with the data and presented through figures and tables for scientific interpretation. The literature review revealed various aspects of IR lacking specific definitions, such as economic, governance, social, and ethical aspects. However, the terms used were similar to IR and environmental impacts, which are vital for policymakers to revise the existing rules and regulations.

Industrial Revolutions

In the 18^{th} and 19^{th} centuries, significant technological advancements occurred in Britain and America, beginning with an agricultural revolution that introduced new practices and developments that increased food production, leading to a global ripple effect. This resulted in people leaving agriculture and moving to cities, where they could obtain suitable food products, sparking the era of urbanization. The demand for other products, such as clothes and non-essential items, also increased, necessitating the development of new technologies to meet the growing demand. This era is called 1-IR, which aims to boost the economy and create new opportunities. However, several drawbacks, including environmental damage, continued to increase during the 2-IR. Conversely, there is optimism that the current technological revolution, 4-IR, will lead to a cleaner, safer world. Although society is wealthy and active in world history, the planet is under unusual stress, and there is a need for urgent and transformative change to address the environmental risks. 4-IR is expected to be the world's most rapid period of innovation, which can help minimize environmental damage.

While advancements in IR-4 lean more towards evaluation than radical transformation, their amalgamation within specific contexts portends significant economic and social ramifications, potentially heralding a revolution [36]. The trajectory towards 5-IR is propelled by rapid technological progress and the evolving integration of human processes, which marks both transformation and vulnerabilities and intertwines society with automated supply chains [37]. The emergence of IR-5 expands the scope of technology-centric IR-4 towards a balanced socioeconomic shift driven collaboratively by humans and technology. Human involvement in this technological revolution is prominently emphasized in IR-5, already shaping future trends. Despite challenges in IR-4 adoption and the perceived lengthy journey toward IR-5, immediate consideration is warranted [38]. IR-5 envisions future industrial trends aimed at prosperity beyond employment, integrating intelligence into daily life through advanced technologies like Explainable Artificial Intelligence, and fostering a data-connected intelligent society [39]. Furthermore, "human-machine symbiosis" embodies a vision of control and automation technologies benefiting all life forms. Introducing a novel perspective, IR-6 proposes a humanized revolution [40]. The following sections outline the negative and positive impacts of IRs.

Environmental Challenges of IRs

Negative Environmental Impacts

Many global environmental issues resulted from or were worsened by the IRs [41]. The challenges of increased air, water, and soil pollution and loss of wildlife habitats can be traced back to human history [42]. IRs have four primary impacts— air, water, and soil pollution and habitat loss [43, 44]. Industrial pollutants ultimately reach the human body through the food chain linked to the carbon cycle (Fig. 2). Industrial waste causes a significant loss of raw materials and energy, and solid waste produced by treatment methods used to clean air and water creates new challenges [45, 46]. Hazardous chemicals in waste negatively impact the environment and the quantity of waste [47]. Industries cause air and noise pollution through their production and supply chain, which affects the environment and society [48]. The major environmental impacts of IRs are discussed in the following sections.

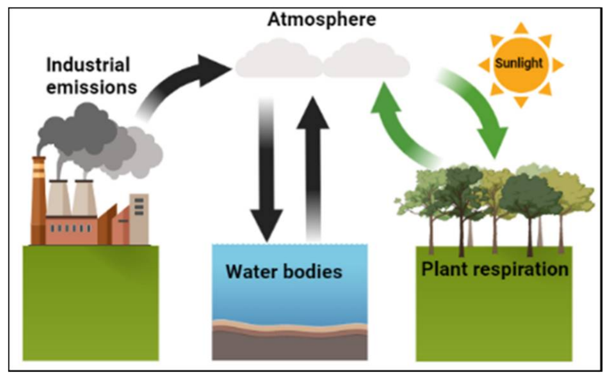

Figure 2. Industrial pollutants to human body through food chain

The biggest problem is air pollution caused by adding numerous harmful chemicals, toxic substances, and particulate matter to the atmosphere [44 - 49]. The emission of GHGs increases the atmospheric temperature and is often considered the prime factor of global warming [50]. This results in the melting of glaciers and an increase in the sea and river water levels, ultimately increasing flood risks [51]. The primary air contaminants released by industry are shown in Fig. 3. Energy consumption is the primary source of particulate matter and CO in the industrial, residential, commercial, and institutional sectors [52]. The manufacturing and extractive industry sector is a critical source of volatile organic compounds (VOC) emissions, responsible for almost 50% of emissions, followed by agriculture significantly [53]. The burning of fuels by industries has continuously increased air pollution since the 19th century, causing higher respiratory illness and death rates [54]. Large amounts of nitrogen and sulfur oxides are emitted into the atmosphere and often converted into nitric and sulfuric acids after reacting with water vapor. This results in acid rain that erodes buildings and monuments, making the soil acidic and reducing plant and animal growth, among other health issues [55].

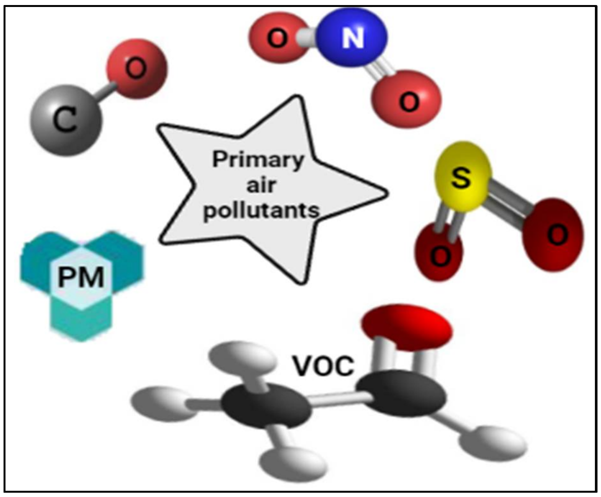

Figure 3. Major air pollutants caused by IRs

The industry is a primary source of water contamination because it discharges extremely harmful pollutants into waterbodies, especially those in and around industrial zones [56]. Industrial pollutants include sulfur, a non-metal detrimental to aquatic life, and asbestos, which has carcinogenic properties [57]. Metallic pollutants, including lead and mercury, threaten human and animal health and the environment. Cleaning contaminants once they enter the environment is difficult because they are non-biodegradable [58]. Oil spilled during shipping and runoff and dumping oil on ocean surfaces cause water contamination daily. Oil spills make up about 12% of the oil that enters the ocean, cause significant problems, and harm aquatic life [59]. The water pollution cycle owing to industrial emissions and receiving bodies is shown in Fig. 4.

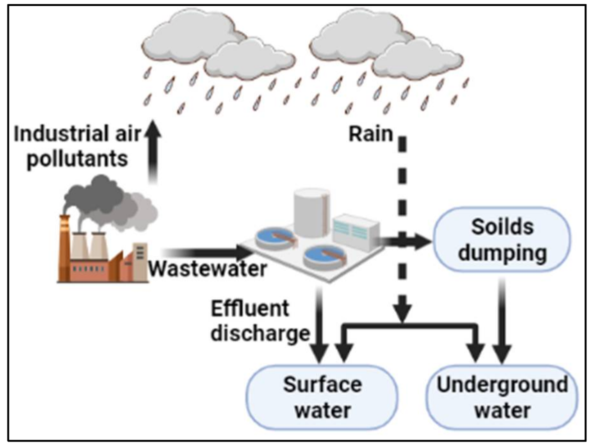

Figure 4. Water pollution cycle caused by IRs

The soil pollution cycle in Fig. 5 shows that the industry contributes significantly to soil pollution. Heavy metals are the major soil contaminants. Other hazardous chemicals leach into the soil and contaminate crops [60]. Soil pollution is mainly caused by xenobiotic chemicals or mining in the natural environment. This is linked to industrial activities and the inappropriate disposal of waste chemicals, such as hydrocarbons, polynuclear aromatic hydrocarbons, solvents, heavy metals, and pesticides [61]. Overall, soil contamination is related to the degree of industrialization and concentration of chemical substances that directly cause health risks or secondary pollution of water sources. It is an uphill task to map and clean up contaminated soil because it is expensive, time-consuming, and requires combining geology, hydrology, industrial chemistry, history, and computer modeling skills [62].

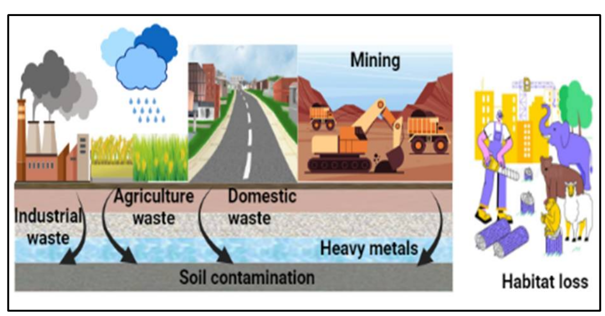

Figure 5. Soil pollution cycle caused by IRs

IR also led to dramatic habitat destruction, as shown in Fig. 5. Ecosystems are destroyed by deforestation, urbanization, infrastructure construction, mineral excavations, and gravel pits [63]. This causes habitat loss and extinction of plants and animals that cannot adapt to their new surroundings or relocate. The United States Environmental Protection Agency monitors more than 80 toxic industrial pollutants, including lead, chromium, asbestos, and dioxins. Regardless of the guidelines, industries are among the worst air polluters worldwide, and nowadays, water and soil pollution is also a challenging issue [64]. The following sections discuss trends in industrial environmental impacts and opportunities to improve environmental quality through IRs.

Trend Change Opportunities (Negative to Positive Impacts)

An overview of the pattern changes from negative to positive environmental impacts of the IRs is presented in Table 1. Despite the negative impacts mentioned in the previous section. The IRs also resulted in economic growth and ensured the availability of goods [65]. To meet the demand of an ever-growing population, using secondary materials produced through efficient recycling and finding alternatives can result in eco-effective impacts [66]. Moreover, industries should produce, store, and use renewable energy for a flexible energy supply and a positive environmental impact by decreasing the demand for fossil fuels [67, 68]. Innovative strategies, such as establishing cooperative value chains and industrial parks with residential areas, allow for future industrial connotations [48, 69]. This approach can decrease industrial waste and convert it into a valuable resource, providing services like sewage water and an extension to their service area, which can also createapositiveimpact [70].

Implementing laws that encourage industries can drive them to adopt the latest technologies, such as emission-sink technologies for cleaning the air and intelligent water treatment. To control noise pollution, industries can use noise-damping infrastructure and noise-reducing production units, equipment, and supply machines to lower the stress levels of people living nearby [71].

Table 1. **A paradigm change from negative to positive IR impacts**

Classification	Negative Impacts	Positive Impacts
Biodiversity	Biodiversity devastation	Create new habitat
Noise emission	Noise pollution	Noise sink
Particulate matter	Air pollutant	Emission sink
Resources & Energy	High demand for resources	Secondary materials, renewable energy
Risks	Source depletion	Emergency supplies
Traffic	Congestion	Transport infrastructure
Waste	Massive residual	Recycling and reuse

Moreover, revised rules and regulations can encourage industries to create new habitats by integrating polishing lakes and/or palm/greenhouses for existing and new organisms [72]. To minimize transport load, the construction of industrial parks should be promoted, where many industries and value chains can share their transportation infrastructure and use standard media supplies [73]. Re-establishing production in residential areas as "urban industries" is a promising strategy that brings customers closer to producers and creates a positive industrial impact. Industries can benefit local communities such as heat and electricity, and places to accommodate people in emergencies [74, 75].

Global Trends
Industrialization Impacts

Acompleteoverviewofthepublicationrat esofenvironmentalimpacts of IRs asasubjectby various publishers from Jan 2011 to May 2022 is presented in Fig. 6. Seven major reference publishers published several studies. The distribution of articles considering the highest and lowest publications is as follows: Elsevier led with 42 articles, followed by Springer Nature (19), MDPI (15), Wiley (12), American Chemical Society (9), Sage (7) and Emerald (3). The literature published by known publishers indicates the importance of IR development and its environmental impacts.

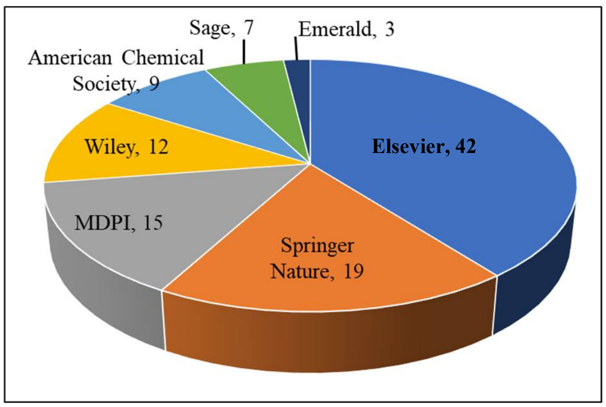

Figure 6. **Literature published by various journals on the environmental impacts of IRs**

The details of published articles by category during the last decadeare presented in Fig. 7(a). This review included 89 articles, 11 proceedings, four early access articles, and three editorial materials. Moreover, the distribution of articles focusing on the environmental impacts of IRs from Jan 2011 to May 2022 showed that the interest in this type of research increased until 2015 (Fig. 7 (b)). A decrease in publications was noticed in 2016 and 2017, followed by a significant increase in 2018 and 2019. The number of published articles increased from 2017 to 2021 in general; it increased significantly in 2020 and 2021, with 16 and 24 published papers, respectively. The number of papers published in 2022 was an exception because the data were collected up to May 30, 2022, and more articles may have been published by the end of 2022. The annual variations and improvements in publishing quantity can be divided into two points. First, attention to the environmental impacts of IRs has increased the number of publications worldwide, especially over the past few years. We confirm that the annual number of environmental impacts of IR-based research papers has increased since 2017. Second, owing to the development and knowledge of IRs, the negative and positive environmental impacts, technological advancements, and stringent policies are the main factors that stress and motivate industries to conduct studies on environmental sustainability.

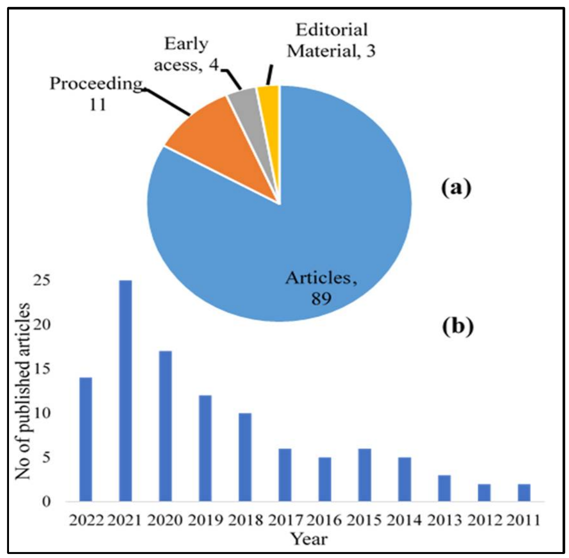

Figure 7. **Literature published by category (a), and year-wise publication rates (b)**

Globally, major countries (Fig. 8) have a strong interest in IR-related environmental impacts based on the publication rate per country, including the USA (18), China (17), the UK (9), Germany (8), and Italy (7). Australia and Spain published five articles, France and India published four, and Austria, Brazil, Portugal, South Africa, and Turkey published three. A little interest was shown by countries such as Japan, Malaysia, Pakistan, and South Korea, which published two articles, followed by Greece, Hungary, Scotland, Sweden, Switzerland, and Ukraine (one article each). These variations in the number of publications contributing to the impact of IRs on the environment are due to the national level's consideration, promotion, and implementation of policies. The proliferation of IR impacts in any region encourages local researchers to solve issues and highlight the positives related to the field, improving knowledge and the value of publications. Although certain regions are ranked high globally, such as the USA, China, the UK, and Germany, a few (developed countries) have been obligated by organizations to implement environmental policies within the last decade. Therefore, these developed countries pay more attention to IR impacts in both positive and negative ways, which can help revise existing policies and develop new strategies for the future. The high level of publishing in a few regions over the previous decade may be because several developing countries are still struggling to implement environmental policies in the industry compared to developed regions that have started efforts earlier than in the last decade.

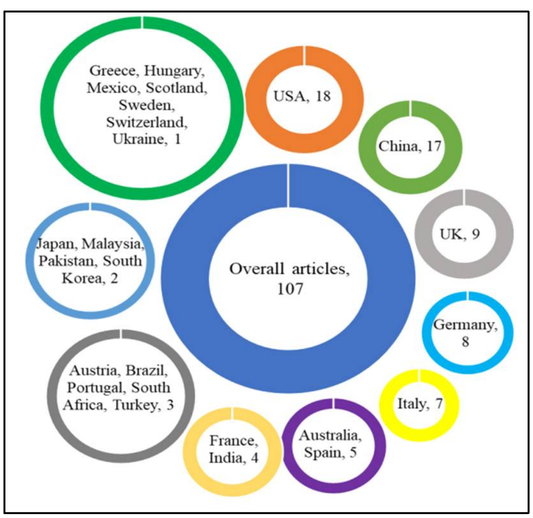

Figure 8. **Literature published by country on environmental impacts of IRs**

Articles were analyzed to reveal the impact of IRs on the environment, as shown in Table 2. Considering the nature of the research category, most of the articles focused on the environmental sciences and studies categories (34) and (19), respectively, followed by green sustainable science technology (13), geosciences, and multidisc-ciplinary (11). Nine articles focused on environmental engineering, and seven on interdisciplinary sciences. Four articles in the categories of physical geography, business, meteorology, atmospheric science, industrial engineering, manufacturing engineering, and water resources were studied in three articles, each of which was included in this study.

Table 2. Research categories of published literature.

Research category	Articles
Environmental Sciences	34
Environmental Studies	19
Green Sustainable Science Technology	13
Geosciences, Multidiscipnary	11
Environmental Engineering	9
Multidisciplinary Science	7
Business	5
Physical Geography	5
Meterology Atmosphere Science	5
Ecology	4
Management	4
Regional Urban Planning	4
Industrial Engineering	3
Manufacturing Engineering	3
Water Resources	3
Agonomy, Automation Control System, Biodiversity, Conservation, Computer Science, Economics, Energy Fuels, Chemical Engineering, Food Science Technology, History	2

In addition, two articles in the literature presented a mixed picture of different categories. The primary area of study was the environmental impacts of IRs, which, of course, is mainly covered by the environmental sciences as per the category of Web of Science. In contrast, multi-disciplinary studies have also targeted this area for analysis because of the continuously increasing environmental issues, accounting for further research.

The relationship between the IRs and the environmental impact research area in each article is considered as a standard of the published article selected for this study, as shown in Table 3. Many articles overlap in the research area, as they have discussed more than one area; therefore, all are included and defined separately. Concerning the targeted research areas of IRs' environmental impacts used by the authors worldwide, the maximum number of publications used environmental sciences ecology and science technology with other topics as their subjects, with 59 and 25 articles, respectively. This was followed by engineering, geology, and business economics studies (19, 12, and 10 articles, respectively).

Table 3. Impact research area on WOS.

Research area	Articles
Environmental Sciences, Ecology	59
Science Technology other topics	25
Engineering	19
Geology	12
Business Economics	10
Meterology Atmosphere Science	6
Public administration	4
Computer Science & Water Resources	3
Agriculture, Automation Control System, Biodiversity, Conservation, Energy Fuels, Food Science Technology, Government Law, History, International Relations, Marine Freshwater Biology, Material Science	2

In addition, six articles addressed meteorology, atmospheric sciences, and public administration; four addressed computer science and water resources; and three highlighted the environmental impacts of IRs with a specific focus. Other categories have been reported in the literature and are accepted for this study. This publishing trend may be due to increased environmental concerns and UN-defined SDG targets for a sustainable future. As ecosystems are linked mainly to the environment, economics, socioeconomic, engineering, and business research areas are closely associated fields.

Strategies for Mitigation and Sustainability Possible Approaches

Numerous organizations evaluate industries based on environmental sustainability criteria [76, 77]. Researchers have introduced different tools, methods, and approaches for comprehensive sustainability evaluations of industries and companies [78]. Several instances of previously applied industries have demonstrated that effectiveness and eco-efficiency have positive impacts and can motivate future industries. It is reported that all the efforts to improve industrial socio-environmental impact in developed countries are due to stringent rules and regulations and public awareness. However, a big challenge is achieving a positive impact on the industry and the whole industry chain in developing countries. Infrastructure must be suitable to support positive effects, and more autarkic industries might be a solution if these conditions are not fulfilled.

Corporate Initiatives

Reducing negative industrial impacts requires fundamental changes in resource utilization from both production and consumer perspectives, focusing on increasing production efficiency. Measuring production efficiency can be an initial step, leading to further development of environmentally effective energy and material consumption. Ideally, every output from one process should become an input for another process within an industry, mimicking biological systems where waste is a nutrient [73, 74]. Industrial parks have already embraced waste reuse by utilizing neighboring industries' outputs as inputs, effectively reducing waste through industrial symbiosis [75 - 77]. By enhancing production process flexibility, adopting high-tech solutions, and considering social and environmental requirements, resource consumption can be minimized while accommodating diverse products, thereby reducing environmental impacts [78]. Various technical and managerial approaches exist to minimize negative industrial impacts [79]. For instance, matrix production, involving substitute production line designs with flexible capacity, can prove beneficial [80]. These agile systems can operate with decentralized intelligence that interacts and communicates effectively with humans [81]. Such technologies support human actions and should be tailored to specific requirements [82]. Installing online sensors enables real-time monitoring and swift response to changes, providing relevant information throughout the production system. Modifying industrial infrastructure is essential for optimizing internal elements and their connections with the environment. Adaptive building infrastructure and modular systems, such as water treatment and air cleaning, can positively impact atmospheric emissions [83]. Therefore, it is crucial to adopt specific strategies that optimize sustainability in the long term across nominated impact dimensions (socioeconomic and environmental). Fig. 9 presents a future outlook for the existing industry, combining recognized approaches that can contribute to a positive environmental impact of IRs.

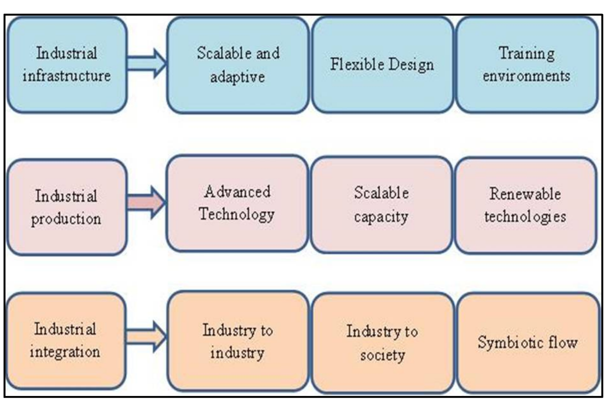

Figure 9. **Strategies for positive environmental impacts of IRs**

Industrial Integration Opportunities

Integrating with industry and society can minimize the environmental impacts of infrastructure, transport, electricity, and water supply. Moreover, it can conserve natural habitats and integrate local biota by recycling materials, recovering rainwater, and generating renewable energy [79, 80]. The infrastructure of a positive impact industry absorbs emissions discharged into the environment and can be used as input [81]. The urban integration of industry gains more importance than the rural sectors. Nowadays, integrated urban industries have many advantages, such as short distances that can ease travelling and improve workers' work-life balance [48]. Moreover, sharing utilities such as energy and other services is closely related to urban integration. Benefits include infrastructure, households, conversion and reuse of waste materials, wastewater treatment, generation of storage of renewable energies, and neutralization of local emissions [82]. Renewable energy (solar, wind, water, geothermal power, or renewable fuels) generation facilities can provide surplus energy [48]. The IoT has become a reality for positive environmental impacts by implementing various instruments to optimize the current and future states of industrial stages. The collection, storage, and processing of operational datasets can provide a clear idea for monitoring and controlling industrial operations through automation [83]. The application of fourth IR technologies combined with cyber-physical systems is aimed at the near future. For example, decentralized artificial intelligence and control devices can communicate and interact with machines and products.

Regardless of technological advancement, a skilled workforce is another critical factor. To achieve better results, realistic experimental training and research environments can assist employees in keeping them updated with technological changes and future requirements [84]. Industries can demonstrate, teach, test, and communicate theoretical knowledge in the natural environment for energy and material efficiency, process optimization, and logistics [85]. Also, they can help individuals design and observe a product by knowledge sharing with society and providing open access to ideas and inventions through scientific knowledge [86, 87]. A review article on the impacts of 4-IR on occupational health and safety presented labor conditions and compensations for workers [2]. Overall, industrial production, industry infrastructure, and integration are major areas of concern for positive industrial environmental impact. The concept of industrial parks, using renewable energy, applying IoT and advanced technologies, and employee training can positively impact the environment.

Environmental Perspectives and Recommendations

Technological innovations

The IRs have brought about significant changes in our worldview but have also contributed to increased environmental challenges. It is our responsibility to address these issues to achieve continuous growth in the future without causing harm to the environment. One approach to resolving these problems is the implementation of advanced technologies that promote resource and energy conservation. The rise of online shopping trends, for instance, has the potential to reduce transportation loads, decrease pollution, and facilitate the online resale of used items, thereby reducing waste generation. Transitioning from fossil fuels to renewable energy sources can contribute to carbon neutrality, and adopting the 4-IR is critical for encouraging emission reduction and environmental protection [25]. Long-term policies should prioritize industrial production and address waste transportation, storage, packaging, distribution, and recycling. The introduction of revised environmental policies, including the regulation of emission limits and technology requirements, as well as the implementation of incentive-based strategies, can help mitigate water and air pollution issues. Policymakers should consider categorizing industries based on their emissions or pollutants and establish specific rules and regulations for each category. This approach underscores the importance of developing tailored approaches to regulating processes and discharges within each industrial sector, ultimately playing a crucial role in achieving environmental sustainability.

National and International Collaboration

Awareness of the link between health and the environment can change the mindset of society to minimize waste production and inspire them to promote the recycling of industrial wastes as their by-products, as well as the conversion of waste to valuable compounds. Although it is practically impossible to establish zero waste-producing industries rather than waste prevention, recycling, and reusing waste should be the priority. To achieve this strategy, policies for raw material procurement, production, and waste discharge must be implemented at national and international levels [88, 89]. The practical approach to decreasing industrial waste containing bioactive and macromolecule compounds by converting them into value-added products is the best possible solution for the environment and economic benefits [90, 91]. Fintech advancements can play an important role in minimizing environmental impacts, as e-commerce has helped a lot by decreasing consumers' physical commute and allowing the availability of many products in one storage, which reduces energy consumption

[92]. Global collaboration is important to achieve sustainable development, minimizing IR impacts on a country, region, and world's society, environment, and economy. In summary, after realizing the IR's environmental impact has had and still has on the environment, there are possibilities to change from negative to positive environmental impacts.

Conclusion and recommendations

This study comprehensively evaluated the environmental impacts of the IRs, highlighting their positive and negative aspects. It examined global trends, and future industry strategies to provide recommendations. The research found that IRs generate substantial waste, leading to air, water, and soil pollution and habitat loss. However, recycling and reusing these waste materials can offer practical solutions for waste reduction, contributing to a circular economy in waste management.

Adopting advanced technologies to improve industrial infrastructure, production processes, and industry-society integration can create positive environmental impacts associated with IRs. The manufacturing sector plays a crucial role in fossil fuel energy consumption. Therefore, it is essential to implement energy-efficient processes and utilize renewable energy sources to foster sustainable economies with minimal environmental footprints.

Legislative bodies should introduce guidelines for green growth and promote sustainable economic development to encourage the adoption of eco-friendly technologies. The strict enforcement of environmental policies, regular policy revisions to address industrial emissions, and increased public awareness are also critical in achieving positive environmental impacts from IRs. Considering industry incentives and economic feasibility is important, and continuous technological advancements are necessary to attain optimal outcomes.

While meeting all requirements for positive environmental impacts may not be mandatory or feasible for every industrial sector, it is sufficient for industries within a specific area to collectively work towards creating positive environmental effects. In conclusion, revising environmental policies can reduce waste production, promote recovery, reuse, and recycling, safeguard the environment, and contribute to a circular economy. Future research should focus on examining the global impacts of IRs to gain a deeper understanding of actions by policymakers, businesses, and researchers to work towards a more sustainable future.

Conflict of Interest

The authors declare no conflicts of interest.

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