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*Research Article*

# The Impact of Digital Transformation on Environmental Sustainability

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Recently, digital transformation is supposed to affect all aspects of human life profoundly. Nevertheless, there is a lack of summaries map digital transformation in the environmental sustainability domain. To address this knowledge gap, this study examines the impacts of digital transformation on environmental sustainability, including both positive and negative effects. Furthermore, the results highlight the transformations that preserve the environment in three main areas: waste management and handling, pollution prevention and control, and sustainable resource management. Based on the literature summary, this study also discusses the opportunities and challenges in this field, which attempts to offer a vision for further research.

## 1. Introduction

Over the past decades, digital transformation has been a substantial focus for many researchers and practitioners. Digital transformation encompasses the profound changes that are happening in every aspect of society, organisations, and industries through the use of digital technologies such as artificial intelligence (AI), big data analytics, the Internet of Things (IoT), blockchain, and other technologies [1].

Digital transformation—the leverage of technologies that influences all aspects of human life—lights up hopes of improving the environment [2, 3]. In the meantime, concerns have been raised about the risks of digitalisation on the environment [4, 5]. The relationship between digital transformation and environmental sustainability is complex, and whether digital transformation helps or hinders environmental sustainability has been the subject of debate within the scientific community.

Despite the complex association between digital transformation and environmental sustainability, a narrowed search for holistic review in this field gives few results. According to our investigations, only a few reviewing articles has been presented in the literature. In [6], the authors conducted a review on the assessments of the environmental impact of digital goods. In this study, they focused on indicators applied by companies to measure the environmental impacts of information and communication technology (ICT) hardware. Meanwhile, in [4], the author conducted a systemic literature review on the indirect environmental effects of ICTs. This study investigated the indirect environmental impact of the application of ICTs in other goods and services and the ecological impacts of these changes.

Another study [7] examined the current digitalisation trend for improving environmental sustainability. The researchers investigated nine cases in various countries using emerging technologies to address climate change adaptation. They asserted that digital transformations could help minimise the impacts of climate change in metropolitan centres. In a recent study [8], the authors introduced a framework that showed how and where such digital transformations occurred in environmental sustainability.

Generally, the studies mentioned above have not given a holistic view of how digital transformations impact the environment. The study [6] explored the direct effect on the environment; on the contrary, the indirect effect had not been mentioned. In contrast, the work in [4] focused on the indirect impact of the application of ICTs on the environment and did not address the direct effects. On the contrary, the authors in [7] concentrated on the impact of digitalisation on climate change adaptation and sustainable development. Meanwhile, in [8], the adverse effects of digitalisation were not mentioned explicitly in the publication.

Against this backdrop, this study aims to identify the impacts of digital transformations on environmental sustainability, both positive and negative aspects. Furthermore, emerging techniques that protect the ecological system in three principal areas, waste management and handling, pollution prevention and control, and sustainable resource management, are also examined.

This study systematically summarises the publications on digital transformation on environmental sustainability. The main contributions of this work are listed as follows:

(i) The positive and negative effects of digitalisation on the environment
(ii) The opportunities that emerging technologies such as AI, big data analytics, IoT, and blockchain could address environmental issues
(iii) The current issues as well as the open research directions of digital transformation in the context of environmental sustainability

The remainder of this study proceeds as follows. Section 2 briefly provides the background information. The research method utilised for this study is presented in Section 3. Next, Section 4 presents the research's main findings and discusses potential challenges as well as further research directions. Finally, conclusions are drawn in section 5.

## 2. Theoretical Background

This section contains the background information necessary to better understand the association between digital transformation and environmental sustainability.

*2.1. Digital Transformation.* There are many attempts to define the term "digital transformation". For example, Westerman et al. stated: "the use of technology to radically improve performance or reach of enterprises" [9, 10], "use of new digital technologies, such as social media, mobile, analytics, or embedded devices, in order to enable major business improvements such as enhancing customer experience, streamlining operations, or creating new business models" as in [11], and "a process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies" as in [1]. Nevertheless, these definitions share a common ground: examining how to use digital technologies to enhance service delivery, change organisational processes and culture, and impact value creation [12].

Although digital transformation is primarily used in a business context, it also affects other sectors such as government organisations and those involved in addressing social challenges by leveraging these existing emerging technologies. In the context of a sustainable environment, digital transformation with emerging technologies such as AI, big data analytics, IoT, and blockchain technology is expected to address environmental issues.

*2.2. Environmental Sustainability.* The sustainability of the environment is an important topic and has attracted the attention of scientists since the 90s. The scientist first coined the term "environmentally sustainable development" at First Annual Conference on Environmentally Sustainable Development [13]. Later, environmental sustainability was conceptualised in the contribution [14]. According to the author, environmental sustainability "seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans".

Environmental sustainability requires research that deals with a wide range of environmental issues, including air and water pollution, waste management, greenhouse gases (GHG) mitigation, renewable energy and energy efficiency, climate change, maintenance of biodiversity, and protection of other natural resources.

## 3. Research Method

The research method described in this study followed the original guidelines as proposed in [15]. The main process consists of four distinct phases: designing, conducting, analysing, and documenting the review. The following protocol asserted the rationale for the study. The main process consists of four distinct phases: designing, conducting, analysing, and documenting the review. The following protocol asserted the rationale for the study: determining the research questions, forming the search strategy, choosing the databases, including and excluding criteria, data extraction, analysis, and reporting of findings.

*3.1. Research Questions.* The research questions addressed by this study are as follows:

(i) Research question 1 (RQ1): what are the effects of digital transformation on environmental sustainability?
(ii) Research question 2 (RQ2): how do digital technologies preserve the environment against pollution and the degradation of natural resources?
(iii) Research question 3 (RQ3): what are the current issues and open research directions?

*3.2. Sources of Information.* The search has focused on selecting papers from the four primary electronic databases: ScienceDirect, IEEE Xplore, ACM Digital Library, and SpringerLink. Apart from the four sources above, we also search in Scopus databases due to its broad coverage of cross-disciplinary fields [16]. Table 1 depicts the primary databases utilised in this study.

Table 1: The main electronic databases utilised in the survey.

| Index | Database | URL |
|---|---|---|
| 1 | ScienceDirect-Elsevier | https://www.sciencedirect.com/ |
| 2 | IEEE Xplore | https://ieeexplore.ieee.org/ |
| 3 | ACM digital library | https://dl.acm.org/ |
| 4 | SpringerLink | https://link.springer.com/ |
| 5 | Scopus | https://www.scopus.com/ |

*3.3. Search Process and Filtering Criteria.* A systematic search of the literature concerning the impact of digital transformation on environmental sustainability was performed. Table 2 shows several criteria defined to discover relevant articles to answer our research questions. The review conducted contains the literature review from 2011 to 2021 in the English language. This range was chosen because it allowed reflection of the study patterns over a substantial period.

In the first search, the author group gathered 570 articles, which were further reduced to 546 based on the articles' titles. Next, the tutorials, short papers, technical reports, conference proceedings, and book chapters were excluded to ensure that all selected studies had undergone consistent revision. After this stage, 319 articles remained. Next, in the phase of skimming abstracts and conclusions, the papers that did not discuss environmental sustainability and were not related to digital technologies were excluded. After scanning the abstracts and conclusions, 160 articles were selected. These papers were examined thoroughly for a final filtering phase. Finally, a total of 106 papers were chosen for further analysing.

## 4. Results

This section presents the study's findings consisting of the general characteristics of the studies and four main domains of investigation, including environmental effects of digital transformation, waste management and handling, pollution prevention and control, and sustainable resource management.

*4.1. Typical Characteristics of the Studies.* In this study, the author group imposed a year restriction that only publications since 2011 were selected. This period was chosen because it gave insight into the study patterns over a substantial period. This period was chosen because it gave insight into the study patterns over a substantial period. Figure 1 displays the number of total published articles after removing the duplication. According to Figure 1, from 2011 through 2015, the number of publications increased linearly. Nevertheless, the pace rose sharply from 2016, with a peak in 2019. This finding suggests that the impact of digital technologies that enable transformations on the environment is a growing area in sustainability research.

This paper focuses on the impact of digital transformation on environmental sustainability. In this manuscript, 106 articles were selected from 2011 to June 2021 for technical review, illustrated in Figure 2. According to Figure 2, the highest number of papers are chosen from the year 2019.

In this study, various digital solutions that could transform the environment have been reviewed. A diversity of digital technologies that enable transformations in different domains of environmental sustainability was examined, such as waste management and handling, pollution prevention and control, and sustainable resource management. Figure 3 represents the statistics of selected papers on different domains of environmental sustainability. According to Figure 3, the number of papers in the three

Table 2: Inclusion and exclusion criteria were utilised in the research process.

| Inclusion criteria |
|---|
| Studies published in press peer-reviewed journals |
| Studies published in the range 2011–2021 |
| Studies were written in English |
| Studies discuss digital technologies affect the environment |
| **Exclusion criteria** |
| Studies were conference proceedings, book chapters, technical reports, short papers, or tutorials. |
| The study was not focused on environmental sustainability |
| The study did not discuss the digital technologies transform the aspect of environment domains |

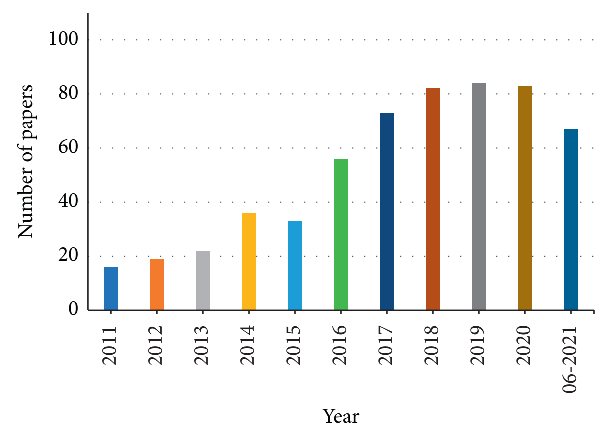


Figure 1: Statistics of the total papers published per year.

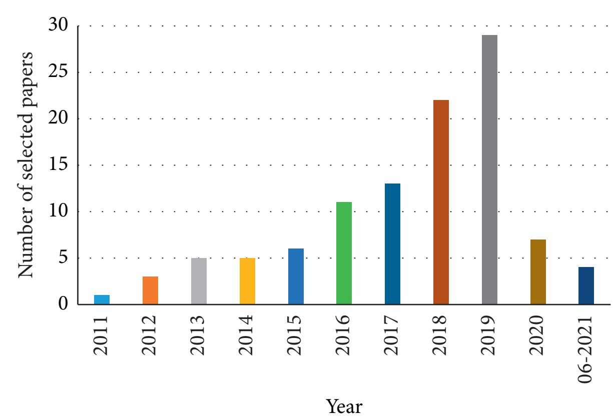


Figure 2: Statistics of the selected papers published per year.

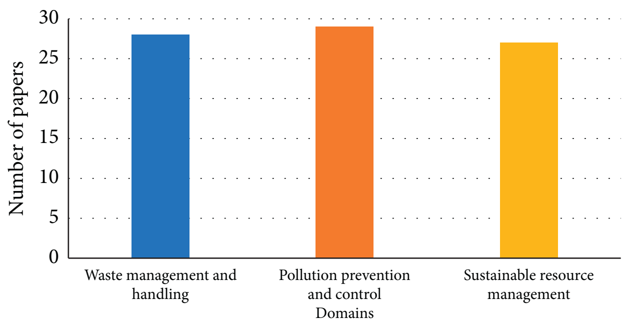


Figure 3: Statistics of the papers based on the environmental sustainability domains.

fields is almost the same. Pollution prevention and control are the areas with a slightly higher number of research regarding digital disruptions, followed by waste management and handling and sustainable resource management.

Even though the chosen papers deal with different digital solutions, four main themes of digital technologies were examined in this study: AI, big data, IoT, and blockchain. The number of papers chosen for every type of technology is formulated in Figure 4. According to Figure 4, applications of AI were utilised in forty-four papers, followed by big data analytics with thirteen papers; IoT was leveraged in eleven papers, the same amount for blockchain. Finally, the combination of different technologies, such as AI and IoT or big data and IoT, showed up in five papers.

### 4.2. *Environmental Effects of Digital Transformation.*

Many optimistic expectations and viewpoints show that digital transformation and innovation could contribute to environmental sustainability. Meanwhile, numerous studies discuss the opportunities and risks that may arise from digitisation and assess the effects of digital technologies on the environment, which can be either positive or negative. Within the scope of this study, the main effects of the direct and indirect environmental impacts of digital transformation were distinguished.

Direct environmental effects are impacts of resources and energy of digital products, i.e., production of ICT devices, energy consumption, and disposal of electronic waste [2, 17]. The mining and extraction of natural resources needed for hardware products are the main contributors to resource depletion and global warming. Furthermore, the raw material mining extraction processes cause other environmental effects, such as heavy metal emissions, acidification, and ground and water service contamination [18]. Other direct environmental impacts that need to be considered are improper collection, recycling, and electrical and electronic equipment disposal. In addition, the greenhouse gas emissions from power generation can also impact biodiversity.

Numerous studies showed that the production phase of ICT goods such as notebooks, smartphones, and tablets dominates the resource depletion impact [19–21]. Meanwhile, the authors [22–24] argued that the production of ICT machinery and devices is among the sources contributing to

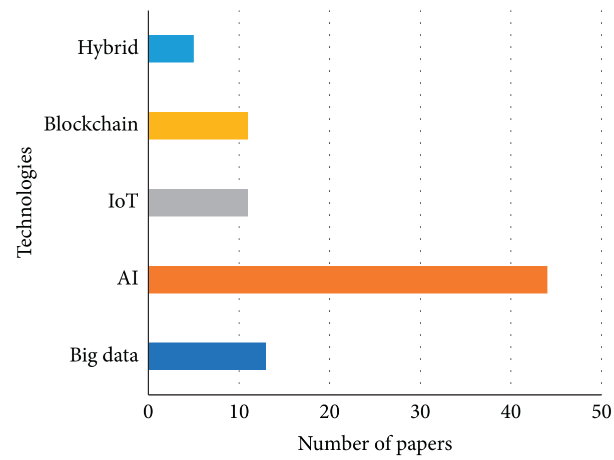


Figure 4: Statistics of the papers based on the technologies.

the increasing levels of $CO_2$ emissions. In other studies [25, 26], the researchers pointed out that waste of electrical and electronic equipment contains dangerous matters, posing significant environmental and health risks if not adequately handled during disposal.

The indirect effects on the environment result from the application of ICTs in other goods and services and the ecological impacts of these changes. Studies assessing the indirect effects on the environment often support the notion that they are desirable for environmental protection [4]. With respect to waste management and handling, digital solutions have been discussed as forecasting the waste generation [27, 28], unveiling resource [29–32] waste, or designing more efficient waste management models [33, 34]. With respect to pollution prevention and control, digitalisation and networking contribute to reducing greenhouse gases [35–37], designing models for predicting emission [38–42], and other applications for controlling environmental pollution. Concerning sustainable resource management, digital technologies open possibilities for energy efficiency [43–47] and exploitation and management of renewable resources [48–51].

Nevertheless, potential adverse effects need to be considered, such as greater energy use by digitalised systems than conventional systems. For example, the authors [52] discovered a unidirectional causal link between ICT and energy consumption. Furthermore, a contribution by the researchers in [53] pointed out that recycling might become more complex with high customisation products. Additionally, the systemic impacts of digital transformation on the environment involve production and consumption patterns, as well as changes in customer attitudes and behaviours. For example, research conducted by [54] reported that the increased usage of the Internet led to an increase in electricity consumption. Furthermore, digitalisation and networking can cause rebound effects because of the increased consumption or triggers growth effects [55].

### 4.3. *Waste Management and Handling.*

The accumulation of waste is a major environmental problem due to rapid urbanisation and population growth. Hence, proper management and handling of waste are essential for any country to prevent pollution and reduce the risks to public health. Digital transformation, with the utilisation of modern technologies, can help develop new coping methods with waste on enormous scales. For example, the authors of [27, 28, 56–61] employed artificial neural networks (ANN) to forecast solid waste generation for efficient management of municipal waste and policy making.

Meanwhile, the researchers of [62] proposed using big data technologies to reduce cost, which led to reduced waste and improved efficiency in the automotive industry. Big data were also utilised to analyse the construction and demolition waste management performance [29–31], as well as identify illegal construction waste dumping [63].

In another study [64], IoT and big data were applied as solutions to manage the waste of electrical and electronic equipment. IoT was also used to treat food waste generated [32, 65, 66] or design a waste collection model in intelligent cities [33, 34, 67].

Other technologies were also transforming the waste management and handling domain. In [68, 69], the authors investigated AI algorithms for improving the efficiency of e-waste collection. Conversely, the researchers in [70] proposed an intelligent waste material classification system, which achieved an accuracy of 87%. On the contrary, in [71–74], the authors proposed to utilise blockchain technology in managing waste as it can offer integrity, resilience, and transparency and audit features in a trusted, decentralised, and secure manner [75].

Table 3 describes the main details of the selected studies focusing on applications of digital technology in waste management and handling regarding the techniques, the main ideas, and their effects.

*4.4. Pollution Prevention and Control.* Environmental pollution with its health impacts is a fundamental issue for ecological sustainability [77]. Therefore, more action is needed to be limiting environmental pollution. Pollution prevention lowers pollution, while pollution control strategies attempt to manage a pollutant after being released and decrease its impact on the environment. Innovative digital technologies find applications in a wide range of areas contributing to the prevention and control of environmental pollution.

In the context of emissions control and monitoring, the utilisation of AI in control systems can help leverage the best available technologies for even better performance. In [35], an application of DSS was introduced to minimise $CO_2$ emissions and energy consumption. Later, in [38], the author investigated and compared decision tree techniques in classifying and predicting emission levels, which showed a promising result.

In [78], the researchers combined an extreme learning machine model and harmony search algorithm to design a model for $NO_X$ emission reduction, which yielded acceptable performance. Furthermore, to estimate $NO_X$ emission, several AI algorithms were also utilised, such as deep bidirectional learning machine [39], deep belief network (DBN) [40], or long short-term memory (LSTM) [41, 42].

Apart from AI, big data also provided opportunities to monitor and control emissions, which assisted environmental sustainability. As in [79], big data were utilised to examine the relationship between carbon emission and economic growth, thereby providing background for governments to formulate emission reduction policies. Other studies applied big data for designing emissions—minimised paths in urban areas [36], investigated the benefits of bike-sharing to reduce $CO_2$ emissions [80], or assisted in selecting the optimal supplier and lot—sizing considering carbon emissions [37].

In the context of solving pollution problems, emerging technologies can help reduce pollution in the environment and achieve sustainability. For example, AI-based models were implemented to model, optimise, predict, and control pollutant issues related to pollutant removal processes [81–83] and analysis and forecast of air pollutants [84–87]. Other digital transformation technologies, such as big data and IoT, also contribute significantly to pollution control and prevention [88–90] (p. 5 in [91]). In [92], blockchain technology was utilised to develop an emission trading system, which was an economic incentive to control environmental pollution.

Last but not least, new technologies also contribute to minimising climate change impacts [93–96] and play a significant role in disaster management [97–99].

Table 4 describes the main details of the selected studies focusing on applications of digital technology in pollution prevention and control regarding the techniques, the main ideas, and its effects.

*4.5. Sustainable Resource Management.* Sustainable resources refer to energy and mineral resources that are either renewable (can replenish themselves) or nonrenewable (eventually depleted). Both renewable and nonrenewable resources need to be carefully managed to reduce resource consumption and pollution while reaching development goals. In terms of sustainable resource management, digital technologies open possibilities for reducing negative environmental impacts of the business through significant improvements in energy efficiency and exploitation and management of renewable resources.

Energy efficiency refers to the method or technique of decreasing energy consumption by using less energy to achieve the same function. Digital solutions can contribute to efficient energy management and reduce the burden on the environment. For example, new techniques were leveraged to forecast the energy consumption [43–45], analyse energy consumption [100, 101], design energy-efficient systems [102–104], or monitor and manage the resources [105–107]. In a recent work [108], the authors proposed an architecture that employ nature-inspired optimization algorithm to optimise the energy in cloud. These technologies transform the decision-making relating to operations, demand response strategies, planning, and energy systems' management.

Regarding the exploitation and management of renewable resources, digital solutions can effectively enhance

Table 3: Applications of digital technology in waste management and handling.

| No. | References | Technology | Main ideas | Effects |
|---|---|---|---|---|
| 1 | [31–38] | AI | Forecasting of waste generation using ANN | Predict waste generation |
| 2 | [39] | Big data | Analytic of real-time data to reduce cost and waste | Reduce waste |
| 3 | [30–32] | Big data | Analysis of the construction waste | Reduce waste |
| 4 | [63] | Big data | Identify illegal waste dumping cases | Reduce waste |
| 5 | [64] | Big data, IoT | Manage the waste electrical and electronic equipment | Efficient waste management |
| 6 | [32, 65, 66] | IoT | Efficient food waste management | Reduce food waste |
| 7 | [33, 34, 67] | IoT | Waste management in smart cities | Efficient waste collection |
| 8 | [76] | AI | Assisted the waste collection with DSS | Efficient waste collection |
| 9 | [68, 69] | AI | Assisted the e-waste collection | Efficient waste collection |
| 10 | [70] | AI | Classify the waste using the DL algorithm | Efficient waste recycling |
| 11 | [72–75] | Blockchain | Blockchain technology in managing waste | Efficient waste management |

Table 4: Applications of digital technology in pollution prevention and control.

| No. | References | Technology | Main ideas | Effects |
|---|---|---|---|---|
| 1 | [35] | AI | Application of DSS to minimise the CO2 emissions | Emission reduction |
| 2 | [38] | AI | Data mining model for predicting emission | Predict emission |
| 3 | [78] | AI | Combined extreme learning machine and harmony search algorithm | Emission reduction |
| 4 | [40–43] | AI | DL algorithm to estimate the $NO_x$ emission | Predict emission |
| 5 | [79] | Big data | Examine the relationship between carbon emission and economic growth | Emission reduction |
| 6 | [36] | Big data | Design emissions, minimised paths for vehicles | Emission reduction |
| 7 | [80] | Big data | Bike sharing to reduce the CO2 emissions | Emission reduction |
| 8 | [37] | Big data | Assisted in choosing the supplier and lot, sizing considering carbon emissions | Emission reduction |
| 9 | [98] | AI | ML methodological approach for flash flood susceptibility modelling | Support disaster management |
| 10 | [94] | Blockchain | Manage carbon emissions | Emission reduction |
| 11 | [94] | Blockchain | Blockchain provides numerous opportunities for reducing emissions from deforestation and forest degradation | Climate change adaptation |
| 12 | [95] | Big data, AI | Rainfall prediction system based on neural networks using meteorological data | Climate change adaptation |
| 13 | [97, 99] | IoT | Managing natural disasters | Disaster management |
| 14 | [82–84] | AI | Optimise the pollutant removal processes | Pollution reduction |
| 15 | [85–88] | AI | Analysis and forecast of air pollutants | Predict air pollution |
| 16 | [88] | Big data | a novel approach for measuring urban air pollution | Pollution reduction |
| 17 | [92] | Blockchain | Emission trading system | Pollution reduction |
| 18 | [90] | IoT, big data | Low-cost IoT devices for monitoring air quality | Monitor pollution |
| 19 | [91] | IoT, AI | Air quality evaluation framework using fixed and mobile sensing units | Monitor pollution |

energy generation and consumption management. In [109, 110], DSS was utilised to select the most promising locations for installing renewable systems based on natural energy sources. Similarly, DSS was used to estimate forest biomass availability for energy production [111] or a hybrid renewable energy system's effective and efficient energy management [48]. Meanwhile, other methods were utilised to predict variable renewable energy generation sources [49–51, 112], design renewable energy systems [113] and microgrid energy markets [114, 115], and develop an IoT-based solution to generate electrical energy from multiple sensors [116]. Controversy, swarm intelligence methodologies were utilised in [117, 118] for optimising the multimode resource-constrained project scheduling problem considering both renewable and nonrenewable resources.

Table 5 illustrates the main details of the chosen references that concentrate on applications of digital solutions in sustainable resource management regarding the techniques, the main ideas, and their effects.

## 5. Discussion

Based on our comprehensive literature review, the detailed answers to the three questions we raised before are discussed and answered.

First, as for RQ1, regarding the effects of digital transformation on environmental sustainability, the aspects have been explored in the available literature. This study distinguishes the main categories of direct and indirect environmental effects.

(i) Direct effects: the production, consumption, and disposal of digital goods impact the environment in diverse ways and put pressure on the environment. The direct effects related to the digital transformation could cause resource depletion, water scarcity, greenhouse gas emissions, and pollution and cause substantial pressures on biodiversity.

(ii) Indirect effects: numerous research studies assess the indirect effects of digitalisation and networking on

Table 5: Applications of digital solution in sustainable resource management.

| No. | References | Technology | Main ideas | Effects |
|---|---|---|---|---|
| 1 | [44–48] | AI | Forecast the energy consumption | Energy efficiency |
| 2 | [100, 101] | Big data | Analyse energy consumption | Energy efficiency |
| 3 | [102] | AI | Design energy-efficient systems | Energy efficiency |
| 4 | [103] | IoT | Design energy-efficient systems | Energy efficiency |
| 5 | [104] | Blockchain | Design energy-efficient systems | Energy efficiency |
| 6 | [105, 106] | AI | Monitoring and management the resources | Energy efficiency |
| 7 | [107] | IoT | Monitoring and management the resources | Energy efficiency |
| 8 | [108] | AI | Optimise the energy cloud | Energy efficiency |
| 8 | [109, 110] | AI | DSS was utilised for selecting the ideal locations to install the system | Increased renewable energy |
| 9 | [111] | AI | Estimate forest biomass availability using DSS | Energy efficiency |
| 10 | [48] | AI | Efficient energy management of a renewable energy system using DSS | Increased renewable energy |
| 11 | [49] | AI | Predict solar power generation using a decision tree | Increased renewable energy |
| 12 | [50, 51] | AI | Predict solar power generation using SVM | Increased renewable energy |
| 13 | [112] | Big data | Variable generation power forecasting | Increased renewable energy |
| 14 | [113] | Blockchain | Designing renewable energy systems | Energy efficiency |
| 15 | [115] | Blockchain | Designing renewable energy markets | Energy efficiency |
| 16 | [116] | IoT, AI | IoT-based system to generate electrical energy from multiple sensors | Increased renewable energy |
| 17 | [117, 118] | AI | SI optimised the multimode resource-constrained project scheduling problem | Increased renewable energy |

the environment and support the notion that they could contribute to sustainable development. For example, digital technology such as AI, big data, IoT, and blockchain is revolutionising our approach to biodiversity conservation, clean energy development, and management of natural disasters. Nevertheless, prospective known adverse effects and uncertainties regarding the application of digital solutions need to be considered, for example, the energy-intensive demand for ICT-enable systems. Additionally, the rebound effects of digital transformation on the environment involve production and consumption patterns, as well as changes in consumer behaviour and attitudes that need further investigation.

Second, as for RQ2, regarding how digital technologies preserve the environment, this study points out that the advancement of digital technologies such as AI, big data, IoT, and blockchain could help alleviate the negative effects on the environment in a variety of ways.

Due to the advancement of AI technologies, AI-based models now impact every field of study. In environmental engineering, AI is implemented to solve the issues related to waste treatment modelling, pollution, sustainable resource management, and other areas. Due to their potential for data mining and feature extracting, AI-based models are extensively used to forecast waste generation and predict concentrations of pollutants and particulate matter, as well as monitor and prevent air pollution. Furthermore, AI was utilised to optimise waste collection routes, locate waste management facilities, and simulate waste conversion processes. Additionally, AI-based systems can also help when reducing the greenhouse gases emitted into the atmosphere. On the contrary, AI was also used for improving the forecasting accuracy of renewable energy.

The big data revolution has led to an information explosion for decades as humans and machines continue to generate large volumes of data at exponentially rates. Given the utility of big data, academia and practitioners have started to integrate these technologies to address sustainable environmental problems. Regarding pollution control and prevention, big data allow monitoring in real time to determine a method to track pollution violations and forecast future pollution. Furthermore, big data analytics enables tracking GHG emissions, reaching renewable energy goals, or designing energy-efficient systems.

Over the years, IoT innovation has transformed everyday objects into intelligent things, with interoperability between them and their environment. The usage of intelligent data-sensing devices opens the opportunity to digitise numerous operations and brings enormous benefits. It is also a facilitator of environmental sustainability research and application. The principal areas of IoT application for waste management involve monitoring, automation, and optimization. This increases the efficiency of waste management, thereby supporting environmental protection. Furthermore, the IoT has immense potential to improve the environment by increasing atmospheric quality, reducing pollution, and sustainably managing resources. This can be achieved by utilising advanced monitoring tools to collect data, and then, the outcome would be used by the decision-making systems.

Blockchain is considered one of the most disruptive inventions of the past decade, potentially impacting many areas of society such as energy industries, financial corporations, and pub sectors [119]. This ledge technology also has the potential to address environmental challenges. For example, it allows the development of efficient waste management systems or the design of energy-efficient systems. Furthermore, blockchain technology has facilitated applications of sharing economy in the energy area. In addition, blockchain-based methods can be deployed to reduce the number of pollutants being released into the environment by utilising a blockchain reward system.

Finally, as for RQ3, general issues that need to be tackled and the research areas that need further development are indicated as follows.

*5.1. Current Issues.* Even though the leverage of digital technologies for environmental sustainability goals has yielded favourable results, there exist general issues that need to be tackled in years to come.

(i) The extraction of mineral resources for ICTs' goods production causes a host of negative impacts on the environment, including resource degradation, land and water contamination, and biodiversity disturbance. Hence, it is crucial to improve the sustainability regulation and its enforcement.

(ii) The volume of e-waste proliferates year by year and becomes an emerging threat to the environment. Hence, reducing e-waste streams and enhancing recycling technology are essential to lowering the environment's burden.

(iii) Digital transformation requires a large amount of physical hardware. All these physical products demand resources and energy throughout their life cycle. Hence, a comprehensive approach is needed to understand the impacts that digitalisation benefits the environmental aspect.

*5.2. Open Research Direction.* Our study has revealed many issues, while some research avenues that should be carried out in the upcoming future years also appeared, as presented below:

(i) To date, few studies have investigated the systemic indirect environmental effect of ICT-enabled solutions. Hence, this is a critical issue for future research.

(ii) In-depth studies are needed to investigate the association of technologies with their resource demands and ecological impact. For instance, the implications of emerging technologies such as blockchain and sensor technology in the environment context have yet to be thoroughly studied.

(iii) Limited research has been conducted on the other digital transformation environmental impact categories except for GHG emissions and energy. Hence, the research community should expand the scope of the impact categories of ecological assessment studies, such as biodiversity disturbance, abiotic resource degradation, and the contamination of land and water.

## 6. Conclusion

The aim of the present research was to examine the impact of digital transformation on environmental sustainability. Specifically, this study focused on how digital technologies preserve the environment against pollution and improve the effectiveness of waste management and handling and sustainable resource management. This study has shown that the advancement of digital technologies such as AI, big data, IoT, and blockchain could help alleviate the negative effects on the environment in numerous ways.

In this study, the direct and indirect effects of digital transformation technologies on the environment were presented. In addition, a review of several techniques applied in different environmental domains aspect, including waste management and handling, pollution prevention and control, and sustainable resource management, were also presented, followed by the challenges and potential future research directions in this field. Overall, this study strengthens the idea that digital transformation has immense potential to achieve environmental sustainability goals. Nevertheless, it also engages a series of challenges, which need more in-depth investigation. To conclude, we believe our study lays the groundwork for future research into the field of environmental sustainability. Future research should be undertaken to explore how digital transformation impacts other related sustainability domains, such as the economy and the social fields.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declares no conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper.

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