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Impact of Digitalization, Big Data, and AI in Society 5.0 on the Four Major Hypotheses and Income Inequality

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Abstract

Sustainable development has become a global priority, with individuals, businesses, and governments working toward the Sustainable Development Goals to address environmental challenges, particularly climate change. However, the increasing severity of climate-related disasters, environmental degradation, and widening income inequality associated with globalization continues to complicate international efforts toward sustainability. These challenges raise concerns about the prospects for coordinated environmental policies between developed and developing countries. In this context, the emergence of Society 5.0, supported by digitalization, big data, and artificial intelligence (AI), presents opportunities to integrate economic development with solutions to social and environmental challenges. These technological advances may provide new insights into longstanding debates in environmental economics, particularly those concerning the environmental Kuznets curve, the resource curse, the pollution haven hypothesis, the Porter hypothesis, and income inequality. This narrative literature review examines research trends and emerging challenges by focusing on highly cited studies published in influential academic journals between 2015 and 2025. Through a synthesis of literature, the review explores how digitalization, big data, and AI are influencing the interpretation and application of established environmental economics hypotheses.

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1. Introduction

As the adoption of industrial robots becomes increasingly widespread globally, the Fourth Industrial Revolution aims to achieve dramatic improvements in productivity through the use of the Internet of Things (IoT) and artificial intelligence (AI); consequently, the production volume of industrial robots and the use of IoT and AI on the shop floor are expanding rapidly [1]. Furthermore, to address pressing environmental issues such as global warming, the Fifth Industrial Revolution is being pursued as a strategy to harness the productivity gains derived from robots and AI, thereby fostering sustainability and resilience [2, 3]. Whilst the impact of IoT and AI on employment was initially a major point of contention, in recent years, the focus of debate has shifted to their environmental impact. The advancement of IoT through the introduction of AI, big data, and digitalization is expected to contribute to decarbonization and pollution reduction by improving efficiency and resource allocation in production and energy use [4, 5]. The transition to renewable energy has the potential to bring about widespread improvements in socioeconomic factors, such as income inequality, energy inequality, human capital, energy education, gender, health, and community [6, 7]. Therefore, if the utilization of AI, big

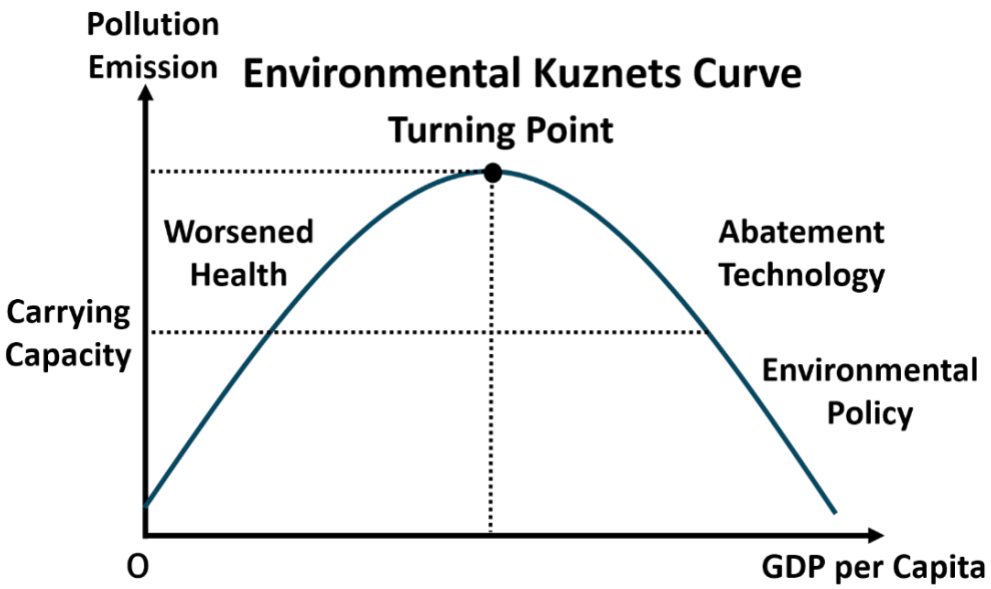


Figure 1. Environmental Kuznets Curve.

data, and digitalization helps to realise a 100 per cent renewable energy system, many of the targets under the Sustainable Development Goals (SDGs) are likely to be met. On the other hand, concerns exist that the use of the IoT and AI consumes vast amounts of electricity, and that the greenhouse gas (GHG) emissions associated with the power supply will accelerate global warming [8, 9]. Recently, the low-level noise generated by data centres—which are essential for AI, big data, and digitalization—has come under scrutiny as such noise is believed to be causing serious health problems for local residents [10].

With the spread of AI and growing attention to the relationship between AI and the environment, environmental economics has discussed four key hypotheses. Taking the Environmental Kuznets Curve (EKC) in Figure 1 as a starting point, these are the Resource Curse (RC), the Porter Hypothesis (PH) and the Pollution Haven Hypothesis (PPH). A synthesis of these four hypotheses is presented in Figure 2. Developing countries with low per capita GDP tend to emit large amounts of pollution during the process of economic development accompanying rapid growth, consequently leading to health hazards caused by environmental pollution. However, once they reach a turning point in their development, investment in pollution abatement and the development of pollution control technologies progress, further contributing to a reduction in pollution emissions. In developed countries, stringent government environmental policies further accelerate this decontamination process, thereby leading to sustainable development. The inverse U-shaped relationship between economic development and pollution emissions is known as the EKC [11]. This EKC may not necessarily hold true if pollution sources are regarded as natural resources. Resource-rich countries that rely on resource rents may squander their export revenues from resources on income redistribution or political corruption, thereby hindering education and innovation and remaining stuck in economic stagnation or underdevelopment; this hypothesis is referred to as the RC [12]. In such cases, even if resource exports are robust, to achieve a transition through education and innovation becomes difficult. Consequently, when GHG emissions and pollution arise during the extraction and production of natural resources, pollution levels tend to increase in tandem with economic development. PC suggests measures to improve this situation; strict environmental regulations encourage companies to develop technologies for decarbonization and pollution reduction, thereby indirectly fostering economic growth through innovation [13]. Innovation driven by environmental regulations implies that the turning point will occur sooner. Therefore, if environmental regulations are strengthened in resource-rich countries and environmental innovation is promoted, decarbonization and pollution reduction in resource extraction will progress, potentially realizing pollution reduction alongside economic growth. Whilst many resource-rich countries are developing nations, one of the catalysts for environmental innovation in these countries is foreign direct investment (FDI). When manufacturing bases in developed countries are relocated to developing countries via FDI to reduce production costs, pollution emissions in the developing countries will be reduced if non-pollution-intensive technologies from the developed countries are transferred to them. This effect is known as the 'pollution halo hypothesis' [14, 15]. Conversely, if

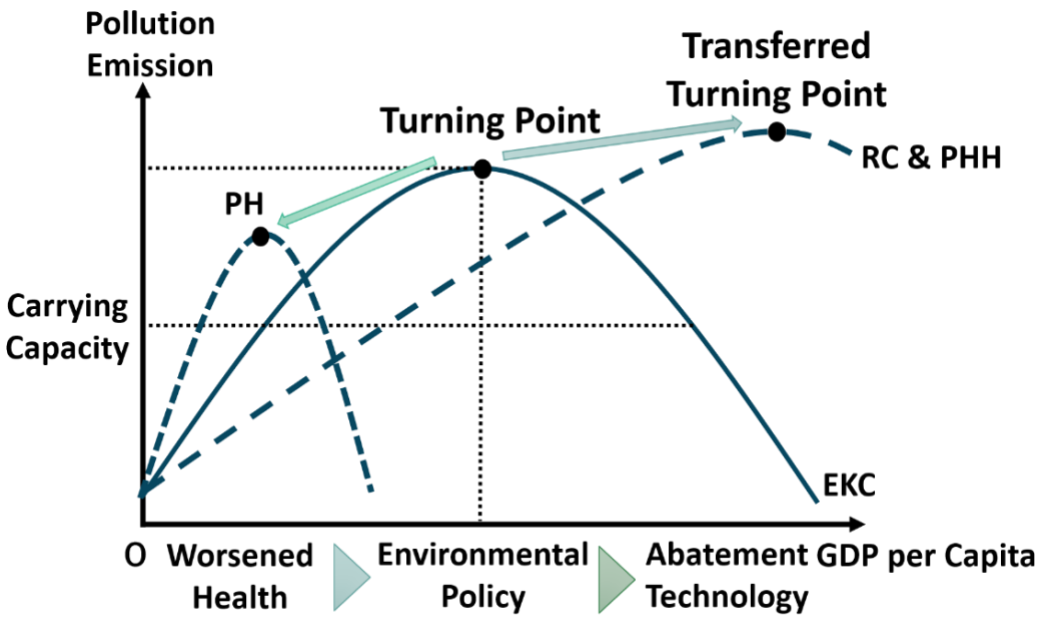


Figure 2. Interrelationship among EKC, RC, PH and PHH.

pollution-intensive firms relocate to developing countries with less stringent regulatory standards via FDI to evade strict environmental regulations in developed countries, their pollution emissions in those developing countries will increase. This effect is known as the 'pollution haven effect'. The 'pollution haven hypothesis' posits that the promotion of corporate relocation through trade liberalization leads to an increase in the relative level of pollution emissions in developing countries compared to developed countries [16].

The pollution haven hypothesis implies geographical inequalities in pollution emissions and environmental quality. In addition to these geographical inequalities, attention is being drawn to the links between income and wealth inequalities on the one hand, and the environment and pollution on the other [17, 18]. In developing countries within the EKC, when environmental pollution arises as a result of economic development, the poor suffer greater adverse effects than the wealthy. This is because the decline in local residents' incomes caused by worsening environmental pollution leads to widening inequality and inter-regional income disparities [19]. When asset inequality—such as in shareholdings—widens due to firms locating in anticipation of environmental regulation costs, and if polluting firms become concentrated in a particular area, pollution emissions will also increase [20]. In such cases, unless redistributive policies and environmental policies that take environmental impacts into account are implemented, environmental pollution driven by income inequality will intensify further [21]. If such stricter regulations spur environmental innovation, the transition may occur sooner, potentially leading to a reduction in pollution alongside economic growth. However, in developed countries, pollution-intensive industries are often in decline; in such cases, workers in these sectors are exposed to the risk of wage cuts or unemployment [22]. In such cases, the tightening of environmental regulations by the government increases the costs of these industries and, consequently, risks widening income inequality through wage cuts or unemployment among workers in these sectors [23]. Workers who foresee this outcome are likely to hesitate to vote for parties that are calling for stricter environmental regulations in elections and will oppose such tightening [24]. In an EKC, this policy choice hinders the reduction of pollution that accompanies economic growth. In countries falling into the RC category, although dissatisfaction with the ruling party is potentially accumulating due to high levels of inequality, income redistribution through resource rents serves to alleviate this political discontent [25]. Thus, inequality can be regarded as a key economic factor linking these four hypotheses.

As outlined above, in environmental economics, EKC, RC, PH, and PHH are key hypotheses that are linked to inequality and interrelated; they have also been explained in relation to economic growth within the framework of the research and development (R&D)-driven growth model [26–31]. However, despite the theoretical mechanisms being elucidated, debate regarding the validity of these hypotheses is ongoing, particularly concerning statistical significance and the magnitude of their effects. When discussion of these

hypotheses first began, IoT and AI were not yet being utilized extensively in production settings; consequently, their impact on these hypotheses was minimal. Nowadays, IoT and AI are being incorporated into industrial robots, and their connection to the environment is beginning to be highlighted; research linking these technologies to the aforementioned hypotheses is also progressing. However, a sufficient body of research that conclusively asserts that IoT and AI are decisive factors in determining the statistical significance of EKC, RC, PH and PHH is lacking, nor can the possibility that other factors are the fundamental causes be ruled out. To conduct a more detailed analysis of these hypotheses, it is essential to organize the four interrelated hypotheses from the perspective of IoT and AI based on existing research.

In addition to several policy recommendations, a number of points for consideration have emerged as future challenges. According to PH, environmental regulations that lead to a short-term rise in operating costs may result in long-term efficiency improvements through industrial upgrading. In this context, developing countries may not have fully achieved industrial upgrading through digitalization yet. Here, the synergistic effects of environmental policy and digitalization tend to promote reductions in GHG and pollution emissions, with ICT and environmental taxes enhancing sustainability. Consequently, utilizing the revenue from environmental taxes to subsidize the digital economy could realize sustainable development through the 'double dividend' of environmental taxation. However, as this decarbonization effect may depend on the methods of digitalization, governments need to use subsidize to steer investments towards appropriate digital projects. With the spread of ESG finance, not only governments but also financial institutions have the potential to support sustainability through digitalization.

Furthermore, the expansion of ICT driven by financial development promotes improvements in energy efficiency through digitalization, which in turn leads to decarbonization. This is because digitalization stimulates green innovation, such as in the field of renewable energy, and encourages consumption and transition to renewable energy. In this context, financial institutions should guide companies towards undertaking investment projects that contribute to decarbonization through sustainable financing. One reason oil-producing countries in the Middle East are accelerating their transition away from resource-based economies is that they are utilizing their oil resources to develop financial markets, whilst applying AI and digitalization. The Asian Infrastructure Investment Bank is also supporting the expansion of renewable energy across Asia through sustainable finance. By implementing such lending strategies, both private and public financial institutions have the potential to help developing countries move away from resource-based economies and resource-based household economies through sustainable finance.

Accordingly, on 29 December 2025, searches were conducted on Google Scholar for the following terms, in order: the EKC, RC, Porter's hypothesis, the pollution haven hypothesis, and inequality. In each case, the three terms 'digitalization', 'big data', and 'AI' were entered as a set to search for each of these hypotheses. The target period was set as the ten-year span from 2015 to 2025. After excluding working papers and emerging journals, the primary focus was on articles published in journals by traditional publishers with at least 100 citations. As a result, 84 articles were selected; however, as some articles cited in this survey for explanatory purposes are distinct from those collected for the survey itself, the total number of cited references exceeds 84. This survey is not a methodological systematic review, but rather a traditional narrative review in which cited papers are selected based on the author's judgement. Whilst Web of Science and Scopus include high-quality papers that have passed rigorous peer review, the process of indexing and publishing papers takes longer than on Google Scholar. As this survey covers the latest academic papers published between 2024 and 2025, Google Scholar has been used here. Furthermore, whilst it has been pointed out that the quality of peer review varies among some emerging journals, there are also concerns regarding citation bias arising from the acquisition of an extreme number of citations. Consequently, we have carefully selected cited papers from journals published by established publishers—which have a reputation for rigorous peer review processes and whose academic influence is widely recognized—to discuss current research trends. In the following sections, the previous research related to AI, big data, and digitalization is organized and summarized in the order of EKC, RC, PH, Inequality and PHH; remaining areas for future research are discussed in the conclusion.

2. Environmental Kuznets Curve as a Starting Point

2.1. Research Trends of EKC

As illustrated in Figure 1, since EKC is closely related to RC, PH and PHH, it provides a useful perspective when discussing its links with AI, big data, and digitalization. A total of 34 previous studies on EKC relate it to AI, big data, and digitalization. In terms of the classification of the analyses, six global analyses cover both developed and

developing countries, and nine focus on a single region, such as Europe; the majority of these concern the EU, whilst others cover Asia and the Middle East. A total of seven analyses of groups of countries, such as the BRICS, G7 and G-20, are noted, and 12 analyses focus on a single country; the vast majority of these concern China, whilst others cover Vietnam, Mexico, and Saudi Arabia. By region, the analyses comprise 16 on Europe, 13 on the United States, seven on the Middle East, 27 on Asia and 10 on Africa. A total of 26 analyses are country-level, whilst all eight provincial or city-level analyses focus on China. Overall, the analyses are not skewed towards any particular country or region, and a balanced range of studies has been conducted. In particular, given the focus on the BRICS countries, and with the inclusion of analyses on South Africa, the number of studies focusing on Africa is not particularly low. However, given the large volume of prior research on China, analyses focusing on Asia account for a significant proportion of the total. Consequently, the empirical findings relating to China have the potential to introduce regional bias into AI, Big Data, and Digitalization with EKC. The countries and regions analysed, analysis period, analytical methods used, and main findings of the prior research are summarised in Table 1.

2.2. Implications from Existing Surveys

An analysis of 2,500 peer-reviewed articles published in the Web of Science and Scopus between 2010 and 2024 revealed that approximately 60 per cent reported positive environmental effects of the digital economy, approximately 25 per cent reported negative environmental effects, and approximately 15 per cent presented mixed or inconclusive results or conclusions [32]. Using panel data from 214 countries, Wang et al. [33] re-examined the N-shaped EKC using panel data from 214 countries, incorporating 12 explanatory variables—including traditional as well as emerging variables such as institutions and risks, information and communication technology, AI, resource and energy use, and selected social factors—and found robust evidence for the existence of an N-shaped EKC. Geopolitical risks, ICT, and food security had a positive effect on per capita carbon dioxide emissions, whilst composite risks, quality of institutions, the digital economy, energy transition, and population ageing had a negative effect; however, the effects of AI, natural resource rents, trade openness, and income inequality were not statistically significant. Taking all variables into account, the inflection points of the N-shaped EKC were US$45,080 and US$73,440.

Although the digital economy generally brings about effects that lead to reduced pollution and environmental improvement, it is difficult to completely rule out the possibility that it may result in increased pollution and environmental degradation. Furthermore, whilst ICT is recognized for its carbon-negative effects, AI and the digital economy have been observed to have carbon-positive effects. Research has noted that ICT contributes to decarbonization by improving energy efficiency in production facilities and in the renewable energy sector [34]. Normally, the energy transition should contribute to decarbonization by promoting the uptake of renewable energy; however, AI and the digital economy consume vast amounts of electricity and water resources, resulting in a high ecological footprint. Furthermore, the radiant heat emitted by data centers contributes to global warming [35]. Consequently, the fact that a carbon-positive effect is observed in the energy transition may be due to the carbon reductions achieved through ICT being outweighed by the carbon emissions generated by AI and the digital economy. Definitions of what constitutes AI, ICT, and the digital economy vary across studies and are not uniform. If AI, ICT, and the digital economy are examined in isolation, their respective definitions may overlap from one paper to another, thereby posing a risk of bias in the results. Therefore, an integrated empirical analysis of these three variables after clearly distinguishing between them is needed.

Given these definitional difficulties, publication bias may be at play in the findings regarding the positive environmental effects of the digital economy; the fact that, should reproducible empirical analyses be conducted based on strict definitions, findings indicating negative environmental effects of the digital economy may increase cannot be ruled out. It is still too early to draw definitive conclusions regarding the environmental effects of the digital economy, and we have reached a stage where its robustness should be examined more carefully. The explanatory variables of natural resource rents, trade openness, and income inequality are each associated with RC, PHH, and inequality, respectively; however, none of them has a statistically significant impact on per capita carbon dioxide emissions. As explained in later sections, statistically significant results have been observed in individual empirical analyses. Consequently, a key unresolved research question is why the results observed in localized analyses are not observed in global analyses. However, unravelling the reasons for this remains an unresolved research challenge.

2.3. The Effects of AI and Digitalization on EKC in Developed and Developing Countries

Whilst resource extraction, energy consumption, and pollution emissions associated with economic growth degrade the ecological footprint, the transition to clean

Table 1. Main results of EKC.

Authors	Methods	Period	Country/Area (S.)	Effect	Results	Others
Wang et al. [36]	Entropy-based TOPSIS, FMOLS, AMG, CCEMG	2000-2020	High-income, middle-income, lower income (81)	AI ⇒ Energy demand/ Resource use ⇒ Environmental damage (+)	High income: AI ⇒ Reduced environmental damage Lower income: AI ⇒ Expanded environmental damage	EKC is confirmed by AI
Wang et al. [37]	FE	2010-2019	World (60)	High AI growth in developed countries	Unstable AI growth in developing countries	The non-linear effects of AI on the ecological footprint
Arshad et al. [38]	ME	2007-2021	EU (27)	Economic growth, ICT, HDI ⇒ Environmental quality (+)	Financial development ⇒ Environmental quality (−)	These synergistic effects ⇒Environmental quality (+)
Adeshola et al. [39]	Dynamic PTR, Pooled mean group estimator	2000-2017	EU (23)	ICT, Environmental tax ⇒ Sustainability (+)	R&D investment, Income per capita ⇒ Sustainability (−)	Reduction effect of ICT on greenhouse gas depends on threshold of tax level.
Dimian et al. [40]	GMM, PCSE, ME	2000-2021	EU (27)	Digitalization ⇒ Greenhouse gas (−) via direct / mediating effects	Digitalization ⇒ Renewable energy consumption	Methods of digitization affects these effects
Khursheed et al. [41]	MMQR, CUP-FMOLS, BA-OLS, 2SLS	2000-2022	EU (27)	Digitalization ⇒ CO_2 (−) ⇒ Sustainability (+)	The synergistic effects of digitalization and government spending ⇒ Environmental quality (+)	-
Yao et al. [42]	OLS, IV, 2OLS, FGLS, Panel QR	1993-2015	OECD, BRICS (40)	Industrial Robot ⇒ CO_2 (−)	Inverted U-shaped relationship between digitalization and CO_2	Reduction effect on CO_2: BRICS > OECD
Ximei et al. [43]	Panel, Causality test	1991-2020	APEC (19)	EKC is confirmed	ICT ⇒ Sustainability (+)	Load capacity factor is considered.
Liu & Mehmood [44]	Panel estimate resistant to slope heterogeneity, CD, MMQR	2000-2021	G-20 (18)	Digitalization, Natural resources ⇒ Environmental Quality (−)	Stable government, Clean energy ⇒ Ecological footprint (−)	-
Chen & Victor [45]	Panel, Two-step System GMM, FGLS robustness checks, DH causality tests	2000-2022	G7 (7)	AI ⇒ Ecological health (−)	Positive effect of AI on Ecological health ⇒ AI×FDI is not statistically significant	-
Chen & Rodger [46]	LIML, DCCE-MG, PCSE, Granger causality tests	1996-2023	G7 (7)	AI ⇒ Ecological system (−) in PSCE	AI ⇒ Ecological system (+) in DCCE-MG	-
Shahzad & Miao [47]	FGLS, DH	1990-2021	East Asia, China (21)	Bilateral trade ⇒ Clean technology ⇒ Sustainable development	Digitalization ⇒ CO_2 (−)	-

Authors	Methods	Period	Country/Area (S.)	Effect	Results	Others
Ridwan et al. [48]	STIRPAT model, ARDL, AMG, CCEMG	2010-2022	Brazil, Russia, India, China, South Africa, Turkey (6)	AI innovation ⇒ Ecological footprint (−)	-	Sustainability-enhancing technological effect
Huang et al. [34]	Panel QR	1990-2022	India, China, Korean, Japan, Thailand (5)	Digitalization ⇒ Green innovation, Energy transition ⇒ Sustainability	-	Large synergistic effects
Sibt-e-Ali et al. [49]	ARDL, QARDL, Panel ARDL, Panel cointegration, DK	1990-2022	United Arab Emirates, Bahrain, Kuwait, Qatar, Oman (5)	EKC is confirmed.	Digitalization, Fintech ⇒Carbon neutrality	-
Bâra et al. [50]	ADSL, Panel ARDL, Wavelet analysis	2003-2018	Turkey, Romania, Bulgaria, Greece (4)	Turkey: Fossil fuels ⇒ Ecological footprint (+) Romania, Bulgaria: Migration processes with pollutants	Greece: A Green process with a rebound effect	The EKC phase diagram varies from country to country.
Wang et al. [51]	Global MINDW-MML model	2011-2018	Provinces in China (30)	Big data ⇒ Green development	This effect depends on Technological development	These effects depend on location, governance, digital financial inclusion
Guo & Yang [52]	FE, ME, TE	2011-2021	Cities in China (286)	Energy efficiency, Green technology ⇒ Greenhouse gas (−) under high digitalization	Under high digitalization, DNOP ⇒ Geological inequality of environment (−)	Brain-drain in low development area ⇒ Geological inequality of environment (+)
Khan et al. [53]	NARDL	1990-2021	China (1)	Digitalization ⇒ Mediating effect on CO_2	-	-
Islam et al. [54]	ARDL, FMOLS, DOLS, CCR	1980-2023	Mexico (1)	ICT ⇒ CO_2 (+)		ICT impacts infrastructure with fossil fuels

Note: S. denotes the sample size. Arrows indicate a causal relationship; A ⇒ B implies that A causes B. The symbols (+) and (−) indicate an increase or decrease in the variable, respectively; A ⇒ B (+) implies that A causes B to increase.

energy systems improves it, and digitalization drives this energy transition. Therefore, digitalization has the potential to bring about EKC. Wang et al. [37], Wang et al. [36], and Yao et al. [42] have demonstrated that EKC can be achieved through AI. In both developed and developing countries, the effect of AI on the ecological footprint is non-linear [37], and the relationship between digitalization and carbon dioxide emissions follows an inverted U-shaped curve [42]. According to Wang et al. [36], whilst the use of AI increases environmental pressure through energy demand and resource consumption, further AI adoption reduces this pressure through improved energy efficiency and the integration of renewable energy, resulting in the observation of the EKC.

However, differences in the effects of AI and digitalization on the environment and pollution can be observed across countries and regions. Where the carbon dioxide reduction effects of industrial robots depend on an economic growth effect, these effects are greater in OECD countries than in BRICS nations [42]. Whilst innovation is a source of growth, if it leads to the development of green technologies—such as pollution reduction and decarbonization—innovation contributes not only to economic growth but also to reducing pollution. Consequently, in high-income countries, the effect of AI in reducing environmental impact is greater [36]. Conversely, in resource-intensive countries, the effect of increasing environmental impact is greater [36]. In regions with inadequate digital infrastructure, the spread of AI and digitalization leads to a worsening of air pollution [55]. When digitalization reinforces energy-inefficient ICT goods and services or low-level green ICT, environmental quality deteriorates [40]. Consequently,

the carbon dioxide reduction effects of industrial robots are greater in industries within the higher quantiles of emissions [42].

Compared with developed countries, the decontamination and decarbonization effects of AI and the digital economy in developing countries are not necessarily self-evident. Liu & Mehmood [44] highlight that the digital economy and natural resources can lead to a deterioration in environmental quality. A possibility exists that digitalization is being utilized for efficient resource extraction, thereby increasing pollution emissions. As globalization progresses, the marginal effect of AI in reducing the ecological footprint is increasing [37]. When resource-rich or developing countries receive FDI as a result of globalization and actively adopt green technologies from developed countries, such globalization contributes to decarbonization and pollution reduction; this is known as the 'pollution halo effect'. However, with regard to G7 countries, even when FDI has a positive impact on ecological health, the interaction term between AI and FDI is not statistically significant [50]; thus, the effect of AI on environmental quality is not necessarily amplified through FDI. Even as globalization takes hold, firms in developed countries prioritize developing countries with a high degree of political stability as investment destinations, taking risks such as nationalization and conflict into account. Consequently, government stability and clean energy are likely to contribute to a reduction in the ecological footprint [44]. However, whilst AI growth rates in developed countries remain consistently high, those in developing countries are volatile [37]. Whether, in developing countries, the decarbonization and depollution effects of AI are being hindered by a decline in AI growth rates, or whether such effects are inherently weak needs careful assessment.

2.4. Effects of AI and Digitalization on EKC in Europe, Asia, and BRICS

Turkey, Romania, Bulgaria, and Greece are at different stages of the EKC: Turkey has a high ecological footprint due to fossil fuel use and urbanization; Romania and Bulgaria are in a transitional phase following structural reforms, during which their ecological footprints remain high; and Greece is at a stage of development where its ecological footprint is declining [50]. However, analyses focusing on EU member states suggest that, rather than observing an EKC resulting from AI and digitalization, these technologies demonstrate significant GHG reduction effects [39–41]. Regarding the relationship between AI, digitalization, and EKC, developed countries exhibit greater carbon reduction and environmental impact reduction effects than developing countries [36, 42]. Given that EU countries have strict environmental regulations by international standards, and because the analysis was limited to regions where these effects are particularly pronounced, the environmental impact of AI and digitalization can be said to have been sufficiently reduced, subsequently leading to the disappearance of the EKC. Instead, complementary effects and mechanisms that enhance the environmental benefits of AI and digitalization have been identified. Digitalization and government spending have complementary effects, and their synergy improves environmental quality [39]. Fiscal policies supporting the transition to a digital economy contribute indirectly to decarbonization. Here, Adeshola et al. [39] demonstrate that ICT and environmental taxes enhance environmental sustainability. If this revenue from environmental taxes were utilized as subsidies for the digital economy, it could contribute to sustainable development through improved production and energy efficiency, acting as a 'double dividend' from environmental taxation. Their analysis demonstrates that, whilst ICT does not contribute to GHG reductions when environmental tax levels are low, it does reduce GHG emissions once environmental tax levels exceed a certain threshold. In other words, the double dividend from environmental taxation may be underpinning the decarbonization effects of ICT.

In an R&D-driven growth model, as monopoly prices based on patents lead to a decline in welfare through underproduction of goods, subsidies funded by a lump-sum tax result in an improvement in welfare [56]. However, R&D investment undermines environmental sustainability [39]; consequently, such subsidies may actually worsen welfare by increasing pollution emissions. In this case, R&D subsidies should be replaced with subsidies for the digital economy to improve welfare. Not only government subsidies but also the financial sector can have both negative-carbon and positive-carbon potential. Whilst financial development may hinder environmental quality, when ICT is combined with human (HDI) and financial development, the resulting synergies mean that financial development actually improves environmental quality [38]. Whilst environmental, social, and governance (ESG) and sustainable finance are expected to contribute to decarbonization as financial instruments, debates continue regarding the validity of their effects due to 'greenwashing' stemming from ambiguous evaluation criteria and inconsistencies in certification methods [57]. When this financial development leads to the widespread adoption of ICT, improvements in energy efficiency driven by digitalization will advance, thereby contributing to decarbonization. This is because, where digitalization

has the effect of reducing GHG emissions, it is linked to green innovation and green technologies—such as those relating to renewable energy—and thus promotes the consumption of renewable energy [40]. However, as these decarbonization effects depend on the methods of digitalization [40], prioritizing the allocation of subsidies towards appropriate digital investments will likely be necessary [50].

In the Middle East, led by Saudi Arabia, countries are rapidly driving forward the transition from oil-dependent economies to fintech-led economies. Drawing on the experience of EU countries, decarbonization is underway in the Middle East through financial development that integrates digitalization and fintech, achieved by appropriately allocating abundant oil resources to the digitalization of the economy. Focusing on how digitalization and fintech enhance the delivery and quality of financial services, Sibt-e-Ali et al. [49] identified EKC in five Middle Eastern countries and demonstrated that digitalization and fintech assist in achieving long-term carbon neutrality. In Asia, ICT is also observed to enhance environmental sustainability in the long term—as measured by carbon dioxide emissions, ecological footprint, and load capacity factor—whilst EKC is also observed [43]. Assuming that renewable energy consumption and green innovation drive digitalization, the latter contributes to environmental sustainability through the synergistic effects of green innovation and the energy transition [34]. A notable feature is that unlike in EU and Middle Eastern countries, decarbonization driven by AI and digitalization may be progressing not through financial development, but via the 'pollution halo effect' resulting from bilateral trade with China. Bilateral trade between China and Asian countries contributes to sustainable development not only through economic integration and the dissemination of clean technologies but also through reductions in carbon dioxide emissions driven by digitalization [47]. In recent years, the China-led Asian Infrastructure Investment Bank (AIIB) has been actively utilizing sustainable finance to support renewable energy and urban decarbonization, primarily in Asia; however, it has yet to achieve the targets it has set [58]. The hope exists that the spread of sustainable finance via the AIIB, facilitated by trade with China, will accelerate decarbonization across the Asian region.

At the international level, somewhat different trends can be observed compared to those at the regional level. In the BRICS-T countries—Brazil, Russia, India, China, South Africa, and Turkey—AI innovation is reducing the ecological footprint in the long term [48]. Wang et al. [59] also demonstrate that, within the BRICS countries, green energy, green finance, green innovation, and digitalization are improving environmental sustainability through reductions in carbon dioxide emissions, a decrease in the ecological footprint, and reductions in PM2.5 levels. However, as synergies with AI and digitalization—such as those arising from environmental policies and globalization—have not been analyzed, further discussion is required to determine whether effective initiatives observed in other regions can be applied in these countries. In particular, with regard to the G7 countries, AI and digitalization do not necessarily lead to improvements in environmental quality. Whilst AI has a negative impact on ecosystems, when differences between countries are taken into account, the overall impact of AI on the environment is positive [46]. Similarly, Chen & Victor [45] find that AI, as approximated by industrial robots, has a negative impact on ecological health. Further investigation is required to determine why digitalization in G7 countries does not necessarily contribute to environmental improvement.

2.5. Effects of AI and Digitalization on EKC in China and Others

In China, digitalization accompanied by green finance strategies in the industrial and service sectors is contributing to reductions in carbon dioxide emissions; however, in China's coastal regions, this digitalization is driving progress towards carbon neutrality more effectively than in the inland and western regions [60]. A common finding in empirical analyses of China is that the effects of initiatives aimed at improving environmental quality—such as environmental regulations and FDI—tend to be greater in coastal regions than in inland and western regions. This is because the latter regions have a higher concentration of resource-dependent cities and pollution-intensive industries. In countries such as Vietnam, Saudi Arabia, and Mexico, which have industries and infrastructure reliant on fossil fuels, digitalization actually increases carbon dioxide emissions through economic growth and other factors [54, 61, 62]. Even at the provincial level in China, AI and digitalization are contributing to decarbonization and the reduction of pollution. A digital economy that enhances sustainability links green practices to economic development and contributes to the preservation of natural ecosystems [63]. Big data contributes to green development, but this is largely attributable to technological progress [51]. Li & Chen [64] confirm the EKC by demonstrating an inverted U-shaped relationship between the adoption of agricultural robots and carbon dioxide emissions from agriculture. In this context, government governance regarding environmental regulations determines the decarbonization effect of robots. This is because the higher the level of formal environmental regulations, the

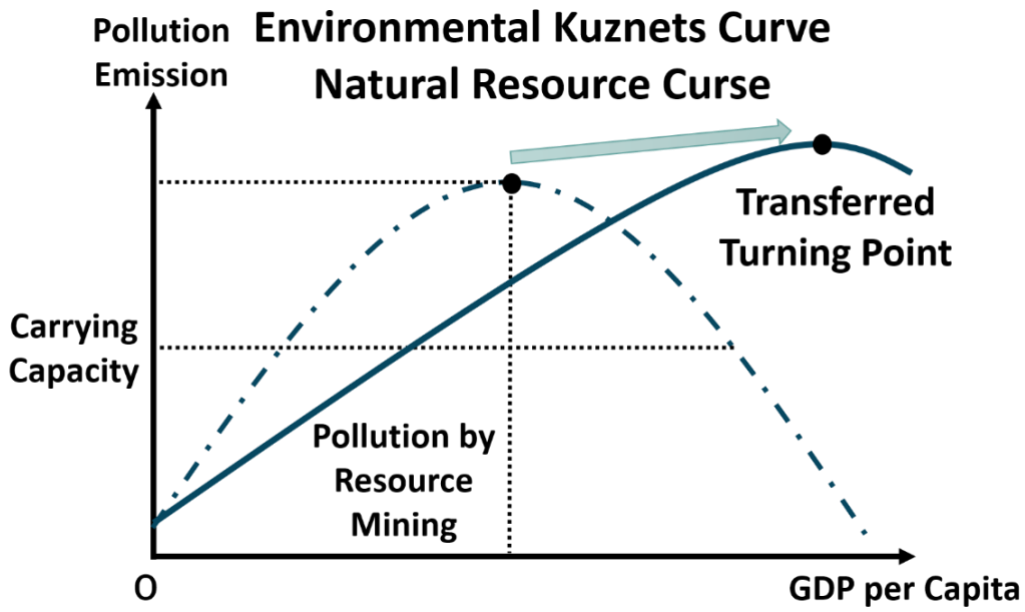


Figure 3. Relationship between EKC and RC.

further to the left the inflection point shifts; conversely, the higher the level of informal environmental regulations, the lower the peak and the further to the right the inflection point shifts. Wang et al. [51] also found that green development driven by big data is influenced by geographical location, degree of environmental governance, and development of digital financial inclusion.

According to a study analyzing approximately 270 to 280 cities, the digital economy and the IoT promote reductions in carbon dioxide emissions and improvements in energy efficiency; however, regional variations in these effects have been observed. The pollution-reduction effects of digital technologies are greater in former industrial regions, highly digitalized regions, and regions with low energy efficiency [65]. Huang et al. [66] also found that the IoT reduces GHG and pollution intensity. Furthermore, whilst the impact of internet-based cities on GHG emissions was more pronounced in inland and western regions, as well as in small and medium-sized cities, such impact was not as pronounced in resource-dependent cities. Guo & Yang [52] identified an inverted U-shaped relationship between digital new-quality productivity and environmental inequality and observed the EKC. Political factors such as environmental policy governance, corruption, and tax evasion are cited as causes of regional disparities in China. For example, Fu & Jian [67] argue that environmental corruption is a key factor influencing the statistical significance of the pollution haven hypothesis via FDI within China. An R&D-driven growth model [30, 68] reveals the theoretical mechanism by which corruption associated with environmental tax evasion leads to pollution haven behavior. Improvements in environmental governance driven by the pollution-reduction effects of digital technology [65], green development driven by the intensity of environmental governance [65], and the earlier attainment of a tipping point through environmental governance [64] all suggest that AI and digitalization have the potential to contribute to sustainable development by improving political factors. Therefore, whether the various benefits of AI and digitalization—such as pollution reduction and improved energy efficiency—may lose their statistical significance due to factors such as corruption should be examined in greater detail.

3. Natural Resource Curse

3.1. Research Trends of RC

A total of 13 previous studies are on RC linked to AI, big data, and digitalization. In terms of the classification of the subjects analyzed, one global analysis covers both developed and developing countries, two analyses focus on EU countries and emerging Asian economies, and four analyses cover the BRICS countries. Of the five analyses focusing on a single country, four concern China and the remaining one concerns the United States. The following regions are covered by the analyses: six in Europe, two in the United States, two in the Middle East, ten in Asia, and four in Africa. A total of five country-level analyses were identified, whilst all four provincial and city-level analyses focus on China. With regard to resource rent (RC), analyses focusing on developing countries predominate over those on developed countries. This is because, in

Table 2. Main results of RC.

Authors	Methods	Period	Country/Area (S.)	Impact of	Impact of	Others
Ahmad et al. [69]	CS-ARDL	2000-2023	Asia (19)	digitalization ⇒ Resource rents (−)	Fintech ⇒ Resource rents (−)	Digitalization×Fintech ⇒ Resource rents (−)
Akcan et al. [70]	PFC tests DK estimators, Panel Fourier causality analyses	2002-2021	BRICS+ (10)	Resource rents 1% ⇒ Economic growth rate − 0.16%	U-shaped relationship between digitalization and RC	-
Kisswani et al. [71]	Panel ARDL	2007-2022	BRICS (5)	Digitalization ⇒ Resource rents (+) in long run	Digitalization ⇒ Resource rents (−) in short run	-
Su et al. [72]	Panel URT, Panel cointegration tests	1988-2021	BRICS (5)	Mineral / Natural resource rents ⇒ trade (+)	Oil rent ⇒ trade (−)	Digitalization ⇒ Sustainable trade (+) Renewable energy ⇒ Sustainable trade (−)
Liang et al. [73]	CS-ARDL	1990-2021	China, Brazil, India, Turkey, Russia, Mexico, Indonesia (7)	Positive relationship between resource rents and economic growth	Growth-enhancing effect of digitalization ⇒ Relationship between resource rents and economic growth (+)	RC is rejected in the long run
Li et al. [74]	Two-unit root tests, ADF, PPT, BHC test, FMOLS, DOLS, CCR	1980-2021	US (1)	Mineral rents, Natural gas rent ⇒ Financial development (+)	Oil rents, coal rents ⇒ Index of financial development (+)	Feedback effect of GDP, Resources, and digitalization on index of financial development
Yun [75]	Structural break URT, structural break OLS, FMOLS, DOLS, CCR	1988-2021	China (1)	Digitalization ⇒ Economic development (+)	Resource rents ⇒ Economic growth (−)	-
Huang et al. [66]	FE, TE	2010-2024	Provinces in China (271)	RC is confirmed	Digitalization finance mediates RC	This mediation effect depends on environmental regulation level

Note: S. denotes the sample size. Arrows indicate a causal relationship; A ⇒ B implies that A causes B. The symbols (+) and (−) indicate an increase or decrease in the variable, respectively; A ⇒ B (+) implies that A causes B to increase.

developing countries, abundant resources tend to be appropriated by vested interests; rather than being channeled into education and investment to promote structural change and industrial upgrading, they are not utilized for these purposes. Consequently, an industrial structure specialized in resource exports is maintained, thereby leading to a tendency for economic development to stagnate. This case is illustrated in Figure 3. By contrast, resource-rich developed countries, such as the United States and the Nordic nations, are reaping the benefits of their resources by channeling resource rents into economic development. The hypothesis that, through democratic governance and private property rights, a distribution system is established whereby resource rents are not appropriated by vested interests but are channeled into education and investment, thereby linking abundant resources to economic growth, is known as the 'curse of political resources' [76].

However, rentier states such as Saudi Arabia and the UAE, as well as Venezuela, provide powerful counterexamples to the 'resource curse'. Venezuela, which is a democracy, achieved oil-led economic growth and subsequently used oil revenues to cover its fiscal deficit, and failed to undertake fiscal consolidation through tax increases or spending cuts. Instead, it sought

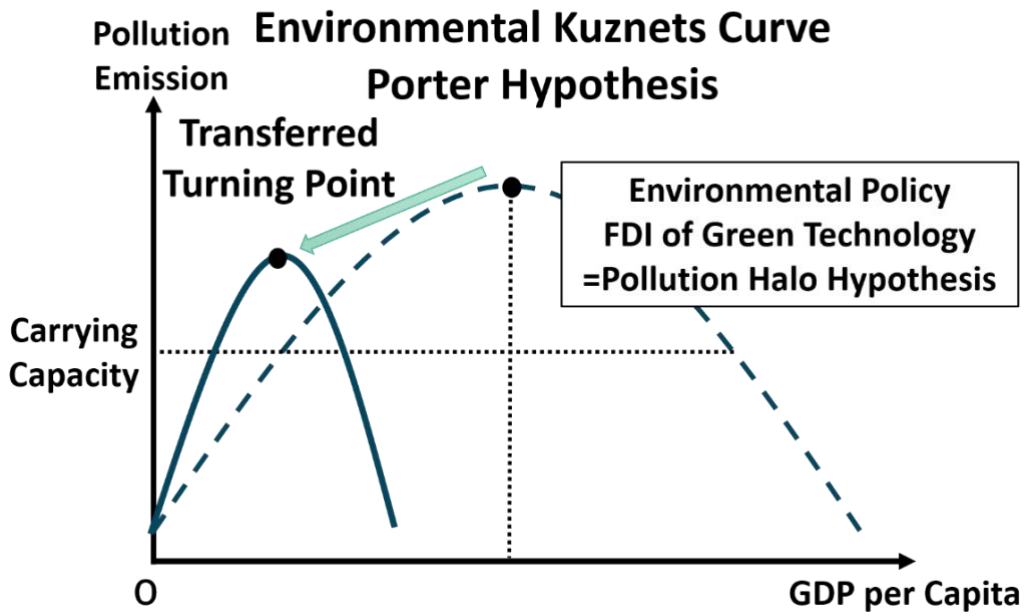


Figure 4. Relationship between EKC and PH.

to maintain its hold on power through redistributive policies aimed at low-income groups. Authoritarian governance led to the persecution and expulsion of oil production engineers, thereby resulting in a sharp decline in oil productivity and output. When international oil prices fell, hyperinflation ensued, and the country lost its former prosperity [77]. In authoritarian states such as Saudi Arabia, whilst political freedoms are restricted, generous income redistribution policies—such as free education and healthcare funded by oil revenues—are guaranteed; by utilizing these funds, these nations are aiming to transition from oil-dependent economies to financial and digital powerhouses and have seen rapid economic growth in recent years [78]. AI and digitalization significantly influence environmental quality through pollution emissions and energy efficiency in the resource sector; moreover, oil-producing countries such as those in the Middle East are beginning to make vigorous use of digital technologies [79]. Therefore, when analyzing how AI and digitalization affect the RC, their consistency with the political resource curse needs to be considered. Figure 3 illustrates a scenario in which the RC delays the transition point in the EKC, leading to prolonged environmental pollution that accompanies economic growth. Prior research, including the countries and regions analyzed, analysis period, analytical methods used, and key findings is summarized in Table 2.

3.2. Effects of AI and Digitalization on RC

Salman & Wang [80] analyzed convergence in natural resource efficiency and the effect of AI on that convergence across the Global South and the Global North and determined that resource efficiency in the Global South is lower than in the Global North. Although overall convergence is statistically rejected, convergence towards three distinct 'clubs' is observed. Efficiency within these clubs increases in the order of Club 1, Club 2, and Club 3. In this context, countries with higher levels of AI tend to converge towards clubs with higher resource efficiency. Whilst the RC is still observed even when AI is taken into account, AI and digitalization are enhancing resource efficiency. In other words, AI and digitalization have the potential to transform the RC into a resource blessing. Other studies also point to the possibility that these technologies may reduce resource rents or help avoid the RC. In China too, four distinct patterns have been observed regarding the effect of the digital economy in mitigating the RC, based on regional or sectoral heterogeneity [81]. Consequently, attention should be focused not on whether AI and digitalization increase or decrease resource rents, but rather on whether they are linked to economic growth.

Given the impact of digitalization on economic development, resource rent (RC) is statistically rejected in the long term [73]; consequently, RC can be overcome through economic growth driven by digitalization. Yun's [75] findings regarding economic development driven by digitalization and the hindrance to growth caused by resource rent complement this policy possibility. Simultaneously, a positive relationship exists between resource rents and economic growth [73]. Whilst digital governance expands resource rents in the long term, it inhibits them in the short term [71]. Consequently, the short-term reduction in resource rents resulting from

Table 3. Main results of PH.

Authors	Methods	Period	Country/Area (S.)	Impact of	Impact of	Others
PH						
Jiang & Jia [82]	GPCA, Panel data, two-way FE	2005-2019	World (71)	High-income: Digital services ⇒ Export of digital service (+)	Middle-income: Digital services ⇒ Export of digital service (−)	Low-income: Digital services have no effect on export of digital service
Liu & Cui [83]	ME	2011-2020	Company in China (1220)	MER ⇒ GTC (+)	MER ⇒ GTFP, GEC (−)	Weak PH is confirmed
Chen [84]	ME, DiD	2011-2019	Company in China (22553)	One standard deviation of intensive CO_2 ⇒ 0.0122		
Chen et al. [85]	Two-way FE	2012-2019	Company in China (2211)	One standard deviation of digital economy ⇒ 0.017 standard deviation of corporate green innovation		
Zhang [86]	Panel data, FE	2011-2021	Company in China (26700)	Digitalization ⇒ Innovation spirit ⇒ Green development This effect is enhanced by environmental regulation		
Wang [87]	SDiD, multi-period DiD, event studies, Staggered DiD	2011-2020	Company in China (17170)	ESG ratings ⇒ Innovation by motivation stimulus and resource supply effects ⇒ Digital innovation Inversed U-shaped relationship between ESG ratings and digital innovation PH is confirmed.		
Bibi et al. [88]	3SLS	1995-2022	Fashion and textiles industries	Digitalization ⇒ Efficiency of operation, Responsivity of market (+) This effect is enhanced by environmental regulation PH is confirmed		
Qian et al. [89]	DiD	2008-2023	Company in China (876)	Carbon trade policy ⇒ Green innovation ⇒ Digitalization PH is confirmed		
Inequality						
Zhou & Du [90]	FE	2015-2022	Cities / Province in China (283 / 30)	Digital government initiatives ⇒ Optimal resource allocation, diffusion of green technology ⇒ Geological inequality of air pollution (−)		
Li et al. [91]	Two-way FE	2011-2018	Cities in China (286)	Digital finance ⇒ Geological inequality of environment (−)		
Xin et al. [92]	XGBoost ML, Entropy-VIKOR model	2005-2020	Cities in China (281)	Digital finance ⇒ Economic growth, Equality of opportunity ⇒ Inclusive growth		
Xin et al. [93]	Panel data, ML, OLS, RF, XG Boost, Light GBM	2011-2020	Cities in China (281)	Digitalization ⇒ Green innovation, Industry upgrading ⇒ Inclusive green growth		

Note: S. denotes the sample size. Arrows indicate a causal relationship; A ⇒ B implies that A causes B. The symbols (+) and (−) indicate an increase or decrease in the variable, respectively; A ⇒ B (+) implies that A causes B to increase. MER: Market-incentive environmental regulation, GTC: Green Technological Change, GEC: Green Efficiency Change, GTFP: Green Total Factor Productivity.

digitalization hinders economic growth. According to Akcan et al. [70], a 1 per cent increase in resource rents leads to a 0.16 per cent decline in the economic growth rate in the long term. On the other hand, in the long term, digitalization may also promote economic growth by expanding resource rents. For this reason, Akcan et al. [70] argue that the effect of digitalization on the RC follows a U-shaped pattern. According to Su et al. [72], while digitalization reinforces the positive effects of mineral and natural resource rents on sustainable trade, oil rents hinder sustainable trade. In the former case, digitalization enables a transition away from the RC through trade; in the latter, however, dependence on resource rents is reinforced, thereby causing countries to remain trapped in the RC.

Middle Eastern countries that are reliant on oil resources are regarded as typical examples of nations trapped in the RC [94]. However, recently, led by Saudi Arabia, these countries have been boosting their economic growth rates by transforming into financial hubs utilizing oil revenues; this strategy relies on fintech integrated with digital technology [95]. The spread of fintech driven by digitalization may help countries avoid the RC by fostering economic growth fueled by resource rents [96]. Taking the interaction between digitalization and fintech into account, Ahmad et al. [69] analyzed the impact of fintech and trade openness on resource rents, and demonstrated that digitalization, fintech, and their interaction term reduce resource rents. In the United States, mineral and natural gas rents exert a statistically significant positive effect on financial development,

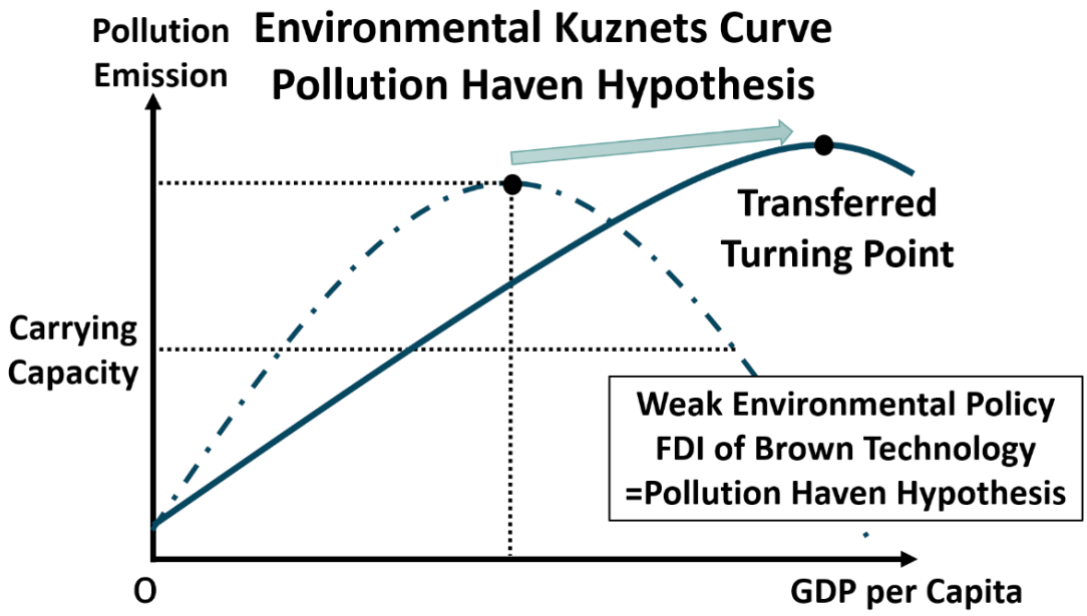


Figure 5. Relationship between EKC and PHH.

whilst oil rents and coal rents have a decisive effect on financial development indicators [74]. Digitalization reduces resource dependence through the upgrading of industrial structures, with the reduction effect being particularly pronounced in western and central China, although heterogeneity across regions has also been observed [97]. Heterogeneity regarding the intensity of environmental regulations has been identified in the mitigating effect of digital finance on resource rents [66]. Consequently, by not only utilizing oil resources for the development of financial markets but also combining this with AI and digitalization, oil-producing countries in the Middle East may be accelerating their transition away from resource dependence. GDP, resources, and digitalization have bidirectional causality with financial development indicators, and feedback effects have also been confirmed [74]. Furthermore, the interaction between fintech and trade leads to a reduction in resource rents [69]. Whilst resource rents from oil and other resources are driving economic growth through digitalization, the utilization of fintech—triggered by trade liberalization—may be initiating a transformation of the resource-intensive industrial structure. The initiatives undertaken by oil-producing countries in the Middle East are likely to provide potential future examples of how the efficient utilization of AI and digitalization can facilitate a transition away from the RC.

4. The Porter Hypothesis and Inequality

4.1. Research Trends of PH and Inequality

A total of 11 previous studies on PH linked to TAI, big data, and digitalization were identified. In terms of the classification of the subjects analyzed, only one study is a global analysis covering both developed and developing countries, whilst the remaining 10 are national-level and firm-level analyses in China. Furthermore, three of these are national-level and sector-level analyses, whilst all eight are firm-level analyses. Of five previous studies on inequality, one is a global analysis, whilst the remaining four are all city-level analyses in China. Compared with other hypotheses, research on PH and inequality is extremely scarce during this period, further highlighting the fact that analysis in this area has not progressed significantly. AI and digitalization have been highlighted as promoting economic growth by reducing resource dependence and pollution intensity through industrial upgrading. Although PH plays a central role in this process, there is a dearth of prior research to substantiate this point; therefore, an urgent priority to compensate for this research gap exists. Figure 4 illustrates a scenario in which PH brings forward the turning point in the EKC, thereby shortening the period of environmental pollution associated with economic growth. The countries and regions analyzed, analysis periods, analytical methods used, and key findings of the prior research are summarized in Table 3.

4.2. Effects of AI and Digitalization on PH

According to Jiang & Jia's [82] analysis covering 71 countries, whilst a high level of digital services has a statistically significant positive impact on exports of digital services, in middle-income countries it has a statistically significant negative impact on exports, and in low-income countries the effect was not statistically

Table 4. Main results of PHH.

Authors	Methods	Period	Country/Area (S.)	Impact of	Impact of	Others
World						
Ke et al. [98]	Pooled regression, GMM	1990-2016	Developing countries (77)	ICT ⇒ CO_2 (−)	ICT×Technological development ⇒ CO_2	PHH is confirmed
Zheng et al. [99]	Panel data	1995-2015	World (47)	Digital economy ⇒ Innovation ⇒ Negative effect of Global value chains on air pollution	FDI ⇒ Air pollution (−)	Very weak PHH is confirmed
Huang et al. [100]	SMM, Static panel data, SAR, SEM, SDM	2003-2020	World (51)	FDI ⇒ CO_2 intensity (−) Pollution halo hypothesis is confirmed	Asia and US are significant	European is non-significant
Zhang & Choi [101]	ARDL	2005-2021	World (52)	Positive relationship between digital trade and green TFP	Negative relationship between FDI and green TFP	Non-linear relationship between digital trade and green TFP
Wang et al. [37]	FE	2010-2019	World (60)	AI ⇒ Ecological footprint (+)	PHH is implied	No robustness by IV
Kumari et al. [102]	GMM, PQR	2000-2023	Asia (31)	Digital financial inclusion ⇒ CO_2 (+)	FDI ⇒ CO_2 (+)	PHH is confirmed
Khan et al. [103]	PQR with an optimization method, MCMC	1996-2020	APEC (18)	Natural resource, Economic growth, Hitech industry ⇒ CO_2 (+)	Innovation ⇒ Energy efficiency ⇒ CO_2 (−)	FDI ⇒ CO_2 (+) PHH is confirmed.
Huo et al. [104]	ARDL, ADF test, Bayesian neural network forecasting	1990-2022	US (1)	Short run: 1% Renewable Energy ⇒ 0.33% CO_2 (−)	Short run: AI ⇒ 18% Efficiency of renewable energy (+)	Long run: 1% FDI ⇒ 0.025% CO_2 PHH is confirmed
China						
Tao et al. [105]	Two-way FE, Spatial regression, Spatial threshold	2005-2020	Cities in China (280)	Digital agglomeration ⇒ Supply chain ⇒ SO_2 (−)	Non-linear effect of digital agglomeration	FDI ⇒ SO_2 (−) Pollution halo hypothesis is confirmed
Hu et al. [106]	FE, ME, Panel TE, SDM	2011-2019	Cities in China (275)	FDI ⇒ Environmental governance (−) PHH is confirmed	Digitalization ⇒ Spatial spillover effect ⇒ Environmental governance (+)	No effect of FDI on E environmental governance
Yuan et al. [107]	Spatial model, ME, Panel TE	2012-2021	Cities in China (267)	FDI ⇒ Environmental pollution (+): Individual fixed-effects model	FDI ⇒ Environmental pollution (−): Individual double fixed-effects model Pollution halo hypothesis is confirmed	Integrated pollution by sulphur dioxide, smoke, dust, wastewater.
Zhang & Yang [5]	TE, SSE	2010-2022	Provinces in China (30)	Data factor aggregation ⇒ Carbon unlocking development (+)	Openness ⇒Carbon unlocking development (−) PHH is confirmed	Spatial spillover effects are non-significant
Zhou et al. [108]	Panel data	2013-2019	Provinces in China (30)	Digital economy ⇒ CO_2, Smog (−)	Space spillover effects	Pollution halo effect is confirmed

Authors	Methods	Period	Country/Area (S.)	Impact of	Impact of	Others
Li et al. [109]	SDM, ME, TE	2011-2021	Cities / Provinces in China (121 / 30)	Digital economy ⇒ Green technology, Energy efficiency ⇒ Pollution (−)	PHH, pollution halo hypothesis are confirmed	-
Cai et al. [110]	FE	2011-2019	Cities / Provinces in China (282 / 30)	Inverted U-shaped relationship between digital economy and green development	Digital economy ⇒ Innovation ⇒ Resource misallocation (−)	Pollution halo effect is confirmed
Gong & Xu [111]	SMM	2013-2021	Cities in China (283)	FDI ⇒ Green transition (−) PHH is confirmed	There is U-shaped relationship between digitalization and green transition	Values of effects are different among area
Qin & Li [112]	Two-way FE, IE, TE	2013-2022	Cities / Provinces in China (31 / 7)	Digital economy ⇒ Innovation ⇒ Green transition	Non-linear effect	Heterogenicity about development, time, types

Note: S. denotes the sample size. Arrows indicate a causal relationship; A ⇒ B implies that A causes B. The symbols (+) and (−) indicate an increase or decrease in the variable, respectively; A ⇒ B (+) implies that A causes B to increase.

significant. Generally, a small number of highly productive domestic firms are responsible for exports to international markets [113]. Consequently, a trend towards polarization can be observed between countries that are able to utilize digital services to improve corporate productivity and those that are not. Bibi et al. [88] analyzed the textile and fashion industries in China and found that operational efficiency and market responsiveness enhanced by digitalization drive industrial upgrading, whilst stringent environmental regulations further accelerate this process. This analysis confirms Porter's hypothesis that whilst raising operating costs in the short term, stringent environmental regulations promote industrial upgrading through efficiency improvements in the long term. Integrating Bibi et al.'s [88] and Jiang & Jia's [82] findings suggests that low- and middle-income countries may not yet have realized the long-term benefits of industrial upgrading driven by digitalization. Furthermore, when green innovation driven by digitalization promotes PH, brown innovation is likely to be inhibited. In such cases, if the short-term decline in brown innovation exceeds the long-term rise in green innovation, PH driven by digitalization may not be observed temporarily. Careful judgement is required to determine whether digitalization inherently leads to PH or whether the effect of promoting PH is masked by the process of temporary technological transition.

Analyses limited to Chinese firms suggest that positive externalities (PH) resulting from digitalization are frequently observed. Liu & Cui [83] confirm the existence of weak PH by demonstrating that market-incentive environmental regulation has a statistically significant positive effect on green technological change. Whilst market-incentive environmental regulation has a significant positive impact on green total factor productivity in the short term, it exerts a significant negative impact on both green total factor productivity and green efficiency change. Owing to these long-term negative effects, no strong PH has been observed. Heterogeneity in these effects has also been confirmed, varying by firm and industry type, location, and level of digitalization. Xin et al. [93] note that digitalization promotes inclusive green growth through innovation and industrial upgrading, with this effect being more pronounced in large and medium-sized cities in eastern China. As the innovation-promoting effects arising from 'motivation stimulus' and 'resource supply' are reinforced by ESG ratings, corporate innovation in digital technologies is also stimulated [87]. However, Liu et al. [114] and Xin et al. [93] find that although green growth progresses rapidly as the influence of the digital economy increases, its pace eventually slows. Consequently, an inverted U-shaped relationship emerges between ESG ratings and corporate digital technological innovation [87]. Qian et al. [89] demonstrate that carbon trading policies have the effect of promoting digitalization through innovation in green technologies. According to Liu et al. [115], China's Environmental Protection Tax Law strengthens the financial foundations of energy-intensive industries by promoting their digital transformation; however, this effect is more pronounced in state-owned

enterprises, and regional variations are also observed in terms of the improvement in financial foundations. Therefore, environmental policies and digitalization contribute to the reduction of GHG and pollution emissions through their synergistic effects.

Digitalization and environmental policies contribute to improvements in firms' green productivity not only through direct effects but also through indirect effects mediated by other factors. Liu & Cui [83] established that firms' investment in R&D and their innovation outcomes act as mediating variables in driving innovation. Chen [84] theoretically demonstrates that the development of low-carbon technologies in high-productivity firms stimulates digital transformation, which mitigates misallocations of capital and labor; the author also empirically shows that for every one standard deviation increase in regional carbon intensity, an increase of 0.0122 occurs. Digitalization stimulates corporate green innovation whilst alleviating financial constraints and environmental uncertainty [85]. In this context, a one standard deviation increase in the digital economy can increase the level of corporate green innovation by 0.017 standard deviations. At both the micro and macro levels, digitalization has a significant effect in promoting green development in regions and firms through corporate innovation, entrepreneurship, and contractual integrity, with environmental regulations further accelerating this effect [86]. Further verification is required to determine whether the positive relationship (PH) observed in the analysis focusing on China is a robust finding also observed in other developed and developing countries, or whether, in countries where no such positive relationship is observed, environmental regulations in the digital economy have simply not yet reached a stage where they sufficiently improve green productivity.

4.3. Effects of AI and Digitalization on Environmental Inequality

No previous studies analyzing the relationship between inequality and the environment in the digital economy were identified in this survey. Instead, Xin et al. [92] found that digital finance contributes to inclusive growth through economic growth, equal opportunities, and the sharing of achievements; furthermore, due to geographical location and population size, digital finance has a greater effect in promoting inclusive growth in inland and western cities. However, the only study identified was by Wang & Xu [116], who analyzed the relationship between inequality and public health. Covering 81 countries, their analysis found that digitalization statistically significantly improves public health in developing countries, with the most pronounced improvements observed in African and middle-income countries. This is because digitalization exerts a positive effect on public health through its indirect effect of reducing income inequality. However, whilst digitalization is considered to generate income and reduce poverty, effects that widen inequality have also been observed; therefore, to draw definitive conclusions regarding its impact is premature. Because digitalization has both inequality-widening and inequality-reducing effects, its impact on the environment via inequality is expected to vary considerably. We are now at a stage where we need to steadily increase the number of analyses examining the relationship between digitalization, the environment, and inequality.

Other studies interpret the geographical distribution of environmental pollution as a form of environmental inequality. Geographical inequality in environmental pollution has the potential to widen income disparities through a decline in labor productivity resulting from deteriorating health. However, our review found no analysis of such causal relationships, and this can be considered a topic for future research. According to Zhou & Du [90], digital government initiatives reduce geographical inequalities in air pollution across cities and provinces through enhanced public oversight, optimized resource allocation, and the diffusion of green technologies. Furthermore, heterogeneity in this effect is observed depending on the types of digital procurement and pollution intensity levels. Guo & Yang [52] identified an inverted U-shaped relationship between 'digital new quality productivity' and 'environmental inequality' and observed the EKC. When levels of the ecosystem, economy, and digital economy are high, 'digital new quality productivity' reduces environmental inequality through improvements in energy efficiency, advances in green technology, and reductions in GHG emissions. When a brain drain regarding R&D occurs from less developed regions, environmental inequality widens. Financial support for digital finance statistically significantly mitigates environmental inequality [91]. This is because its pollution-reduction effects are greater in regions with higher levels of environmental pollution than in those with lower levels, thereby narrowing regional disparities in environmental pollution. Furthermore, the inequality-reducing effect of digital finance is greater in regions with strong local government governance capacity and high environmental preferences. As such, environmental inequalities are strongly correlated with PHH; one of the challenges is to examine pollution-avoidance behavior within China by including FDI and trade liberalization as explanatory variables.

Regarding the inequalities associated with the digital economy, one can point to the digital divide in terms of convenience and usage time in the context of digital device usage [117]. At the macro level, whilst digitalization has no significant impact on income inequality in the early stages of development, it tends to widen income gaps as economic development progresses, only to narrow them again through further economic growth. This is because, in regions with a high proportion of highly skilled workers, digitalization leads to wage increases, whereas in those where digitalization is underdeveloped, it leads to wage decreases [118]. Based on these empirical findings, when the wages and incomes of the relatively high-income groups increase through digitalization, a reduction in inequality may strengthen environmental awareness, leading to a shift towards renewable energy and a reduction in GHG emissions. Conversely, when digitalization leads to a decline in the wages and incomes of relatively low-income groups, the widening of inequality may cause the Engel coefficient to rise across the economy as a whole; if this results in a shift towards fossil fuels, GHG emissions are likely to increase. Beyond this channel, the digital divide and inequality influence pollution emissions, whilst pollution emissions may also have a reciprocal effect on the digital divide and inequality. Clarifying the relationship between the digital economy and inequality and examining its links with EKC, RC, PH, and PHH can be regarded as a major policy challenge in the run-up to the forthcoming Society 5.0.

5. Pollution Haven Hypothesis

5.1. Research Trends of PHH

A total of 28 previous studies on PHH linked to AI, big data, and digitalization were identified. In terms of the classification of the subjects analyzed, six were global analyses covering both developed and developing countries, and two focused on a single region, such as Asia or Africa. One study analyzed a group of nations, such as APEC, and 18 focused on a single country; however, with the exception of one on the United States, all of these focus on China. Furthermore, all 17 of the provincial and municipal-level analyses also focus on China. Overall, a bias exists in the selection of subjects for analysis, with the majority focusing on China. As China exhibits a polarization between the eastern coastal regions—which have high levels of economic scale, educational attainment, FDI, environmental regulations and governance—and the western inland regions—which have lower levels of these factors—observing pollution-avoidance behavior within Chinese provinces is easier. Although analyses of PHH focusing on EU countries were noted, such as that by Candau & Dienesch [119], no previous studies linking PHH to AI, big data, and digitalization were identified. Consequently, determining whether the findings of PHH analyses focusing on China can be observed at the regional or global level is difficult, and we must await further research in this area. Figure 5 illustrates a scenario in which PHH delays the transition point in the EKC, resulting in prolonged environmental pollution accompanying economic growth. The countries and regions analyzed, analysis periods, analytical methods used, and key findings from the previous studies are summarized in Table 4.

5.2. Effects of AI and Digitalization on PHH in Europe, Asia, and America

In a comprehensive survey of environmental Kuznets curves, trade openness is identified as a key explanatory variable in testing the pollution haven hypothesis [33]. Another important explanatory variable is FDI. According to Zheng et al. [99], the negative effect of participation in global value chains (VCs) on air pollution is amplified by the digital economy. This is because the digital economy reinforces the air pollution-reduction effects of participation in global VCs through industrial upgrading and technological progress. In this context, whilst the positive effect of FDI on air pollution implies pollution leakage, its coefficient is only 0.003 at the 10 per cent significance level, which is very small. If pollution-intensive multinational enterprises establish themselves in host countries via FDI, air pollution will worsen. However, if labor input in pollution-intensive sectors declines and labor shifts to clean and green sectors, air pollution will improve. Through these opposing effects, the impact of FDI on air pollution may be offset, thus reducing statistical significance and resulting in smaller estimated values. Wang et al. [37] also observed the pollution escape hypothesis; however, the effects of FDI on the ecological footprint are quite weak, with coefficient values of -0.002, -0.001 and 0.000 at both the 5 and 10 per cent significance levels, and statistical significance even disappears following robustness analysis using the instrumental variables method.

The discovery of the pollution haven hypothesis by Ke et al. [98] is also relevant to the EKC. Whilst ICT reduces carbon dioxide emissions, the interaction term between ICT and technological development actually increases those emissions. In the pre-industrialization stage, the pollution-expanding effect of FDI gives rise to the PHH; however, following the early onset of a turning point brought about by technological development, in the post-industrialization stage, the pollution-reducing effect of FDI gives rise to the pollution halo hypothesis. In Zhang & Choi's [101] time-series data analysis, the PHH is also observed; however, both their effect and statistical

significance are low. Due to the 'pollution haven effect', the long-term relationship between FDI and green total factor productivity growth is negative; however, at the 1 per cent significance level, the coefficient is –0.002, and furthermore, statistical significance disappears when using the instrumental variables method. Even when the data are divided into developed and developing countries, the relationship between FDI and green total factor productivity remains negative at the 1 per cent significance level; however, as the coefficients are –0.0007 and –0.0175 for developed and developing countries, respectively, the effect is again quite small. The fact that, due to the moderating impact of education, the effect of FDI on green total factor productivity becomes negative at the 1 per cent significance level is noteworthy. This result suggests that the prolongation of the inflection point due to education may encourage the 'pollution haven effect' of FDI. Unlike FDI, a non-linear relationship exists between digital trade and green total factor productivity. In developing countries, human capital reinforces the positive effect of digital trade on such productivity, whereas in developed countries, human capital inhibits that positive effect.

Huang et al. [34] examined Asia, Europe, and the United States, and found that a high level of e-government development reduces carbon dioxide intensity. Furthermore, geographical spillover effects were observed, and e-government development in neighboring countries also reduced carbon dioxide intensity in the recipient country. However, this effect varies by region: whilst the reduction effect can be confirmed in Asian countries, such effect is not statistically significant in Europe, the US, and the West. This analysis reveals the PHH as, at the 10 per cent significance level, FDI reduces carbon intensity by only 0.026 or 0.032. However, regional differences are also observed in this case: the effects are statistically significant in Asia (0.190) and the US (0.017), but not in Europe. These results suggest that the transition to a green economy through digitalization may be more pronounced in Asia than in Europe or the US. By contrast, Kumari et al. [102], who focused on Asia, arrived at the opposite conclusion. Specifically, they found that digital financial inclusion significantly increases carbon dioxide emissions and confirmed the existence of a 'pollution haven' (PHH) via FDI. As different definitions of digitalization used in various analyses may alter the detection of the 'pollution haven hypothesis' and the 'pollution halo hypothesis,' caution is warranted when interpreting these results.

Among the 18 APEC economies, excluding Brunei Darussalam, Taiwan, and Papua New Guinea, Khan et al. [103] found that the consumption of natural resources, economic growth, and high-tech industries have a positive effect on carbon dioxide emissions, whilst improvements in energy efficiency driven by science and technology exert a negative effect on carbon dioxide emissions. As the positive effect of FDI on such emissions is statistically significant, the pollution haven hypothesis is confirmed. However, the negative effect of the interaction term between FDI and natural resources on carbon dioxide emissions is statistically significant. This is because domestic firms engage in excessive consumption of fossil fuel-based energy compared with multinational corporations, thereby increasing carbon dioxide emissions. In this context, FDI and trade liberalization could serve as policy instruments to circumvent the RC. According to Huo et al. [104], a 1 per cent increase in renewable energy in the United States will reduce carbon dioxide emissions by 0.033 per cent in the short term. Provided that carbon pricing and innovation continue, the expansion of renewable energy is projected to reduce carbon dioxide emissions by 15 per cent by 2040 in the long term. In this context, AI has the potential to contribute to decarbonization by improving the efficiency of renewable energy by up to 18 per cent. However, as a 1 per cent increase in FDI leads to a 0.025 per cent rise in carbon dioxide emissions in the long term, a positive health-harm (PHH) effect has also been observed. Regarding PHH driven by AI and digitalization, the coefficients and statistical significance of FDI and trade openness on pollution and carbon dioxide emissions are small; moreover, significant regional variations exist, and obtaining conflicting results within the same region is not uncommon. Currently, determining whether AI and digitalization promote or prevent PHH is difficult.

Given that the spread of digitalization risks causing a dramatic increase in e-waste, we should examine the potential for the 'Waste Haven Hypothesis' (WHH) arising from digitalization. Plastic waste, which is a source of microplastics, is difficult to recycle in developed countries; consequently, it is exported to developing countries—particularly in Southeast Asia, centered on China, where waste disposal regulations are lax—thereby giving rise to the WHH [120, 121]. Because e-waste containing precious metals is disposed of through chemical processing, it causes greater environmental pollution and health hazards than plastic waste, and informal waste disposal is further exacerbating these impacts [122]. Whilst the leading explanation for international trade in e-waste disposal is based on PHH, new channels have also been identified, such as large-scale processing by specific companies or organizations at hubs concentrated within a particular region [123]. At

present, attention is focused on decontamination and decarbonization driven by digitalization; however, the negative aspects of environmental pollution caused by e-waste are still under analysis. With the spread of the digital economy on the horizon, the relationship between the digital economy and e-waste should be analyzed more vigorously.

5.3. Effects of AI and Digitalization on PHH in China

As demonstrated by the negative impact of digital technology on carbon intensity through an increase in patent applications [109] and of supply chain digitalization on pollution emissions through improved resource allocation and green technology innovation [124], the decarbonization and depollution effects of AI and digitalization have been confirmed at the provincial level in China; however, a considerable number of analyses merely mention the 'pollution leakage' effect without providing further detail. According to Xu et al. [125], the integration of digital technologies leads to industrial decarbonization through energy optimization and marketisation in the industrial sector and has a statistically significant positive effect on carbon lock-in within that sector. This effect depends on spatial spillover effects and heterogeneity is observed, with the effect being more pronounced in the inland, western, and island regions, in that order. However, the impact of FDI on carbon lock-in is positive but not statistically significant. This is attributed to the offsetting of two opposing effects: the 'pollution haven effect' in the host region and the 'pollution halo effect' in that region, which propagate to surrounding areas via spatial spillover effects.

Yuan et al. [107] also found that the digital economy reduces pollution emissions in a statistically significant manner through green technological innovation and industrial upgrading and also reduces environmental pollution in neighboring cities via spatial spillover effects. Furthermore, geographical heterogeneity is observed. Whilst the digital economy significantly reduces environmental pollution in eastern and central cities, it does not do so to a significant extent in western cities. In this context, the digital economy has a more negative impact on the environment in resource-dependent cities than in non-resource-dependent cities, thus suggesting that digital technology may be being diverted towards improving the efficiency of polluting extraction techniques rather than towards energy efficiency. Only in the individual fixed-effects model is the PHH confirmed, as an increase in FDI significantly increases environmental pollution by 1.118 (at the 10 per cent level); however, the results from the pooled ordinary least squares (OLS), time fixed-effects model, and time and individual double fixed-effects model are all statistically insignificant. On the other hand, according to maximum likelihood estimation, an increase in FDI reduces environmental pollution by a factor ranging from 1.575 to 1.953, at the 5 per cent to 10 per cent significance level, implying the 'pollution halo hypothesis'. In this analysis, compared with the other studies cited, the coefficient of the effect of FDI on pollution is higher and meets the significance threshold. These results may depend on the definition of pollution emissions, which combines multiple pollutants such as sulphur dioxide, smoke, dust, and wastewater. Whether these results remain unchanged when the analysis is broken down by individual pollutants needs to be examined.

Compared with the PHH, the pollution halo hypothesis yields a more significant and somewhat larger effect. According to Cai et al. [110], the digital economy reduces misallocation of resources through improvements in technological innovation, resulting in an inverted U-shaped relationship between the digital economy and green development. In this context, FDI exhibits a pollution halo effect on green development, with coefficients of 0.0028 and 0.0030 at the 1 per cent and 5 per cent significance levels, respectively; however, this effect is very small. The digital economy's effects on reducing carbon dioxide and smog emissions, as well as its spatial spillover effects depend on its mitigating effects, which support the promotion of technological innovation and the synergistic management of carbon dioxide and smog [108]. In this context, the digital economy in the eastern region has a positive effect on the efficiency of carbon dioxide and smog management; the digital economy in the western region has a greater effect on reducing carbon dioxide emissions; and the digital economy in the central region is consistent with the overall trend. As FDI reduces carbon dioxide emissions by only −0.248 at the 1 per cent significance level, this suggests a pollution halo effect. According to Tao et al. [105], digital industrial agglomeration significantly reduces sulphur dioxide (SO_2) emissions through supply chain resilience and has positive spillover effects. In this context, FDI reduces sulphur dioxide (SO_2) emissions by -0.0232 at the 1 per cent significance level, thus confirming the pollution halo hypothesis.

Compared with the pollution halo hypothesis, PHH has only a small and non-significant effect. Gong & Xu [111] find that between 2013 and 2021, whilst the digital economy increased from 0.077 to 0.205 and industrial green transition expanded from 0.262 to 0.573, the digital economy exerted a U-shaped effect on industrial green transition. This effect is 0.585 and 0.320 in the eastern and central regions, respectively. FDI exerts a negative

effect of just 0.001 on industrial green transition at the 1 per cent and 10 per cent significance levels; whilst this supports the pollution haven hypothesis, the effect is small. Zhang & Yang [5], who demonstrated the statistically significant positive effect of data factor aggregation on carbon unlocking development and its significant positive spillover effect, revealed that openness—approximated by the total volume of goods imports and exports—hinders carbon unlocking development within a range of –0.164 to –0.209 at the 10 per cent significance level. Although this result implies the pollution haven hypothesis, it is not robust. According to the heterogeneity analysis, a pollution halo hypothesis of 0.074 at the 10 per cent significance level is observed in the West, whilst a pollution haven hypothesis of –0.209 at the 5 per cent significance level is observed in the North-East. Furthermore, neither the East nor the Centre is statistically significant, and spatial spillover effects are not significant in any case.

However, according to Hu et al. [106], FDI reduces environmental governance performance by as much as 0.008 at the 1 per cent significance level, supporting the pollution haven hypothesis. The digital economy significantly improves environmental governance performance in urban areas through green technological innovation and the optimization of industrial structures. Furthermore, through spatial spillover effects, the digital economy also improves environmental governance performance in neighboring cities, with this effect being more pronounced in the eastern region. Consequently, FDI may be hindering the efficiency of urban environmental governance. Here, Li et al. [109], who demonstrate the pollution-reduction effects of the digital economy through the promotion of green technologies and improvements in energy efficiency, observe that both the 'pollution halo hypothesis' and the 'pollution haven hypothesis' are associated with FDI. This is because, in a threshold model, the digital economy has a pollution-spreading effect at low levels of FDI and a pollution-inhibiting effect at high levels of FDI. Furthermore, the pollution halo hypothesis may occur when the digital economy promotes digital or green transitions.

According to Li et al. [109], the 'Comprehensive Demonstration City of Fiscal Policies for Energy Conservation and Emission Reduction' pilot program statistically significantly promotes corporate digital transformation through the promotion of green technology innovation, demand for green environmental information disclosure, and the driving force of green financial development. However, when controlling for the city, a 1 per cent increase in FDI significantly inhibits digital transformation by -12.8700. Qin & Li [112] also found that the digital economy statistically significantly promotes industrial green transition through technological innovation. In their baseline regression analysis, the coefficient for trade openness is –0.0002 at the 5 per cent significance level, which indicates the presence of the PHH effect. In resource-dependent cities such as Huaibei (Anhui) and Pingxiang (Jiangxi), where environmental regulation levels are low, the low regulatory standards can be interpreted as creating an incentive to maintain price competitiveness by attracting pollution-intensive firms through FDI, thereby hindering the green transition. China is a country where the PHH is easier to analyze, not only because of its large number of researchers but also due to its geographical characteristics and socioeconomic structure; consequently, the PHH resulting from AI and digitalization is greater than in other countries. However, even when capitalizing on these characteristics, challenges remain regarding the significance of the respective hypotheses and relatively low coefficient values. In future analyses focusing on China, attention to identifying the factors that hinder the significance of each hypothesis and the attainment of high coefficient values, and considering whether the results possess the generalizability to be applicable to other countries and regions may be worth attention.

6. Conclusion

As the Fifth Industrial Revolution progresses and the adoption of AI, big data, and digitalization advances, the impact on the environment is becoming too significant to ignore. As these cutting-edge information technologies are closely linked to innovation, trade, FDI, and energy, they have the potential to exert a major influence on key hypotheses in environmental economics—namely EKC, RC, PH, and PHH. However, although these hypotheses were proposed long before the widespread adoption of cutting-edge technologies, debates continue regarding their statistical significance and the magnitude of their effects. With this issue remaining unresolved, the digitalization of the socioeconomic sphere is advancing and beginning to affect the significance and impact of these hypotheses. In the future, it will be necessary to carefully distinguish whether AI, big data, and digitalization are decisive factors influencing these hypotheses, or whether we are overlooking the decisive influence exerted by traditional variables. Understanding the recent research trends will provide valuable insights for future research. To achieve this objective, we conducted a narrative survey, selecting 84 papers, primarily those with 100 or more citations over a ten-year

period from 2015 to 2025—based on the author's judgement.

In line with the discussion in this survey, caution is still warranted regarding the impact of AI, big data, and digitalization on EKC, RC, PH, and PHH. First, the varying definitions of digitalization used in the analyses may alter the significance and estimated values of these hypotheses; therefore, it is necessary to verify the robustness of the findings in the face of changes in definition. Second, although AI growth rates in developed countries remain consistently high, those in developing countries are volatile. Therefore, it is necessary to carefully ascertain whether the decarbonization and pollution-reduction effects of AI are hindered by a decline in AI growth rates in developing countries, or whether such effects are inherently weak. Third, developing countries generally have lower levels of environmental governance than developed countries due to factors such as corruption. In this context, it is necessary to examine in detail whether the various effects of AI and digitalization, such as pollution reduction and energy efficiency improvements, have lost statistical significance or have resulted in underestimated estimates due to corruption and other factors. Fourth, as there is still relatively little research on PH and inequality compared to other hypotheses, attention should be paid to publication bias, which may lead to underestimation. PH is a key hypothesis that influences outcomes such as accelerating the tipping point for the EKC or promoting the pollution halo effect in PHH. The extent to which AI, big data, and digitalization influence this hypothesis is likely to have knock-on effects on the results of the other hypotheses. Furthermore, as digitalization has been observed to have both poverty-reducing and poverty-increasing effects, it should be borne in mind that the impact of digitalization on the environment via inequality is likely to continue to vary significantly. Clarifying the impact of AI, big data, and digitalization on EKC, RC, PH, and PHH will help promote the compatibility of a digital society with a sustainable society.

Finally, what has been clarified, what remains unclear, and what challenges remain for the future? In the context of EKC, the use of AI is generally contributing to the reduction of carbon dioxide emissions and the improvement of environmental quality. Whilst much of this involves promoting the introduction and development of renewable energy and clean technologies, further clarification is needed regarding the identification of other factors and specific channels. On the other hand, in the context of RC, the impact of AI and digitalization on resource rents remains unclear. We are currently at a stage where more empirical analysis needs to be accumulated, and it is difficult to draw any provisional conclusions. With regard to PH, corporate-level analyses focusing on Chinese firms predominate, whilst analyses at the national or multi-country levels remain insufficient. More careful consideration is required as to whether the PH observed in Chinese firms can also be observed in firms in other countries and whether it holds true at the national level. As digitalization has a significant impact on inequality, this relationship is likely to affect the environment as well. However, regarding this important issue, we must await further developments. The positive relationship between digitalization and PH has generally been confirmed. However, its statistical significance remains low, and the effect is also quantitatively quite small. Therefore, a key challenge for the future is how to enhance its significance and robustness. By addressing these limitations, it is hoped that the impact of digital transformation on sustainability can be identified, and that the realization of a sustainable society can be promoted through effective policy measures.

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Abbreviations for empirical analysis methods:

2SLS	: Two-Stage Least Squares
3SLS	: Three-Stage Least Squares
ADF	: Augmented Dickey–Fuller
AMG	: Augmented Mean Group
ARDL	: Autoregressive Distributed Lag

BA-OLS	: Bias-Adjusted OLS
BBC	: Bayer and Hanck cointegration
CCEMG	: Common Correlated Effects Mean Group
CCR	: Canonical cointegration regression
CD	: Cross-sectional dependence
CS-ARDL	: Cross-Sectional ARDL
CUP-FMOLS	: Continuously Updated Fully Modified OLS
DCCE-MG	: Dynamic Common Correlated Effects Mean Group
DH	: Dumitrescu–Hurlin
DiD	: Difference-in-Differences
DK	: Driscoll Kraay
DOLS	: Dynamic Ordinary Least Squares
FE	: Fixed Effects Model
FGLS	: Feasible Generalized Least Squares
FMOLS	: Fully Modified Ordinary Least Squares
GMM	: Generalized Method of Moments
GPCA	: Global Principal Component Analysis
IE	: Intermediary Effects Model
IV	: Instrument Variable
LIML	: Limited Information Maximum Likelihood
MCMC	: Markov Chain Monte Carlo
ME	: Mediating Effect Model
MINDW-MML	: Minimum Distance to Weak Efficient Frontier – Meta-Frontier Malmquist Luenberger
ML	: Machine Learning
MMQR	: Method of Moments Quantile Regression
NARDL	: Nonlinear Augmented Distributed Lag
OLS	: Ordinary Least Squares
PCSE	: Panel-Corrected Standard Error
PFC	: Panel Fourier Cointegration
PPT	: Phillips-Perron Tests
PQR	: Panel Quantile Regression
PTR	: Panel Threshold Regression
QARDL	: Quantile Autoregressive Distributed Lag
RF	: Random Forest
SAR	: Spatial Autoregressive
SDM	: Spatial Durbin Model
SDiD	: Synthetic Difference-In-Differences
SEM	: Structural Equation Modeling
SMM	: Spatial Measurement Models
SSE	: Spatial Spillover Effect Model
STIRPAT	: Stochastic Impacts by Regression on Population, Affluence, and Technology
TE	: Threshold Effect Model
URT	: Unit Root Test
VIKOR	: Vlsekriterijumska Optimizacija I KOmpromisno Resenje
XGBoost	: Extreme Gradient Boosting

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