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The Impact of Digital Transformation on Environmental Sustainability: An Econometric Study of a Sample of Arab Countries, 2005–2024

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Abstract

Purpose- Amid the accelerating digital transformation, the pace of resource exploitation has significantly outstripped its renewal capacity, leading to escalating environmental challenges. In this context, technological innovation has become a cornerstone for achieving two intertwined goals: environmental protection and economic and social development. With growing emphasis on environmental responsibility, digital transformation emerges as crucial for attaining environmental sustainability goals. Despite the positive contributions of digital technologies to environmental sustainability, they also entail negative environmental impacts. Thus, do Arab countries benefit from digital transformation in achieving environmental sustainability, or does it have adverse effects on the environment through increased carbon dioxide emissions?

Design/Methodology/Approach – This research paper relies on a sample of 14 Arab countries, selected due to the availability of primary study data from the World Bank's database. It employs the extended STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology) to investigate the impact of digital transformation on environmental sustainability, utilizing the ARDL methodology data to analyze the short- and long-term dynamic relationships between variables in panel data. Additionally, the study adopts a fixed effects model to demonstrate whether the relationship between digital transformation and environmental sustainability follows an inverted U-shape.

Findings – The analysis shows that digital transformation in Arab countries has a positive impact on environmental sustainability in the long-run. The estimated model reveals that an increase in digital transformation will lead to a 1.05% reduction in carbon emissions through investment in digitalization and green technology. Digital transformation can also reduce energy consumption through smart grid solutions and artificial intelligence by facilitating the integration of renewable energy, reducing reliance on fossil fuels, and paving the way for a transition to a low-carbon economy. Moreover, the relationship between digital transformation and Arab sustainability follows an inverted U-shape.

Research limitations/implications – The study originally intended to cover all Arab countries; however, owing to difficulties in obtaining comprehensive data on digital transformation and environmental sustainability indicators for every country in the region, the analysis was limited to 14 countries. Consequently, we recommend that future research broaden the sample to include a larger set of countries beyond the Arab region. Future work should also consider incorporating mediating variables—such as governance quality, energy mix, and green innovation—to examine the transmission channels of the observed effects.

Practical implications–This research contributes to a deeper understanding of the role of digital transformation and innovation in environmental sustainability by leveraging technology in the environmental sector and transforming the environment into a source of sustainability and preservation for future generations. Integrating technology with environmental systems leads to the development of innovations that enhance environmental sustainability, such as cloud computing, the Internet of Things (IoT), artificial intelligence, big data analytics, and renewable energy technologies. It highlights for policymakers that digital transformation may initially produce negative impacts on environmental sustainability, but over time and in the long-run, positive results begin to emerge as a result of exploiting digital technologies and developing eco-friendly solutions that promote efficient use of natural resources and reduce waste, thereby making a significant contribution to achieving environmental sustainability. Policymakers and environmental regulatory bodies in Arab countries can benefit from these findings to optimally utilize digital technologies for enhancing environmental sustainability.

Social implications– Digital transformation raises societal awareness of environmental sustainability through digital solutions, encourages community participation in eco-friendly initiatives, creates new job opportunities in renewable energy and the circular economy, and drives youth toward green entrepreneurship.

Originality/value–This study explores the potential long-term impacts of digital transformation on environmental sustainability, considering it among the first studies to employ the extended STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model alongside the panel ARDL approach to uncover short- and long-term effects of digital transformation on environmental sustainability across 14 Arab countries.

Keywords Arab countries, digital solutions, digital transformation, environmental sustainability, panel ARDL approach.

1. Introduction

The world faces enormous environmental challenges, as the ever-increasing population growth, urbanization, industrialization, mining, and rapid development—alongside associated socio-economic factors and the unsustainable use of non-renewable resources—represent the primary causes leading to a decline in environmental quality with respect to ecological sustainability, food safety, and animal health. (Temmakoon, Jamadari, & Wattuhewa, 2024)

Greenhouse gas emissions resulting from human activities, such as fossil fuel combustion and deforestation, lead to rising temperatures and climate change impacts across various parts of the world. (European Commission , 2025) Global greenhouse gas emissions reached a new record high in 2024, after increasing by around 3 percent compared to 2023.

The power sector was the largest contributor to emissions at 15.6 Gt CO2e (27 percent), followed by transport (8.4 GtCO2e, 15 percent) and industrial energy (6.5 GtCO2e, 11 percent). (STATISTA, 2025) In light of the rise in carbon emissions, environmental sustainability is an imperative necessity to preserve the environment and ensure the continuity of life.

Environmental sustainability has become, since the year 2000, one of the Millennium Development Goals (MDG), specifically the seventh goal.) BAHMED (2017 ‘ It represents the deep-rooted driving force that connects the three systems in sustainable development, indicating that it is a prerequisite condition for economic, social, and environmental systems. This marked the beginnings of formal interest in sustainable development, which is based on three pillars: economic, social, and environmental. A sustainably managed environmental system should maintain a stable base of natural resources, increase renewable resources, and include agricultural land productivity to avoid depletion within the evolution of sustainable development. (Altalibi & Hussein, 2018, p. 360)

The term "environmental sustainability" was probably first coined by scientists at the World Bank. Originally, the term "environmentally responsible development" was used (World Bank, 1992) Subsequently, "environmentally sustainable development" was employed (Serageldin & Steer, 1993)Finally, the concept of environmental sustainability was developed.

Definitions of environmental sustainability are numerous. The Organisation for Economic Co-operation and Development (OECD) made an important contribution to the concept through its *Environmental Strategy for the First Decade of the 21st Century* The strategy sets out four specific criteria for environmental sustainability: (ORGANISATION FOR ECONOMIC CO-OPERATIONAND DEVELOPMENT, 2001)

- Regeneration: The efficient use of renewable resources, without allowing their use to exceed their long-term natural regeneration rates.
- Substitutability: The efficient use of non-renewable resources, limiting their use to levels that can be offset by substitution with renewable resources or other forms of capital.
- Assimilation: Ensuring that releases of hazardous or polluting substances into the environment do not exceed its assimilative capacity, taking into account concentrations, time and location.
- Avoiding irreversibility: Preventing irreversible adverse effects of human activities on ecosystems, and safeguarding the natural processes capable of maintaining or restoring the integrity of these ecosystems.

Sphera, a global company specializing in sustainability, environment, and governance management solutions, defines environmental sustainability as the responsibility to conserve natural resources and protect global ecosystems to support health and wellbeing, now and in the future. Since many decisions impacting the environment are not felt immediately, a key element of environmental sustainability is its forward-looking nature. (Sphera, 2025)

Environmental sustainability is essential for the survival and well-being of both present and future generations. It aims to ensure that the resources necessary to sustain human life, including food, water, and shelter, remain available without depletion. It also seeks to protect other forms of life in order to preserve ecological balance. Moreover, it is crucial for addressing the major challenge of climate change, which has severe consequences for human life and the environment alike. (Asha , Vyshnavi , Shlok , & Patnala , 2023)

Environmental sustainability is influenced by various determinants, with digital transformation emerging as a key driver. Digital transformation refers to the adoption of advanced digital technologies to fundamentally reshape services and business models, centering on the use of disruptive innovations to boost productivity, foster value creation, and enhance societal welfare. (Schilirò, 2024, p. 72) Digital transformation is a double-edged sword in promoting environmental sustainability, as it offers opportunities to reduce consumption and improve efficiency, but it also raises challenges such as increased energy use and electronic waste. Digital technologies, including artificial intelligence (AI), big data analytics, mobile technologies, Internet of Things (IoT), and social platforms, contribute to beneficial positive advancements in both society and industry. Companies are currently relying on artificial intelligence (AI), the Internet of Things (IoT), and big data analytics to implement sustainable business practices aimed at reducing carbon emissions and minimizing other forms of environmental waste. (Asif , 2023)

Digital transformation affects environmental sustainability both directly and indirectly; however, the nature of these effects.

The direct effects related to digital transformation may cause resource depletion, water scarcity, greenhouse gas emissions, pollution, and place significant pressures on biodiversity.)Thanh (2022 ،. As digital technologies become ever more deeply woven into everyday life, the environmental footprint of the digital economy is expected to increase markedly. For instance, the global stock of Internet of Things (IoT) devices is forecast to nearly double from 15.9 billion in 2023 to over 32.1 billion by 2030; this rapid growth will not only drive-up energy demand—worsening issues such as carbon emissions and reliance on fossil fuels—but also significantly expand the volume of electronic waste produced. (Apurva, Snehal , & Girish, 2024)

Indirect (or second- and higher-order) effects refer to additional environmental impacts arising from the application of digital technologies and services across various economic sectors, extending beyond the ICT sector's direct footprint. These effects can be either beneficial or detrimental to the environment. Positive indirect effects that reduce emissions or other environmental damages are often termed "enabling effects," "abatement," or "avoided emissions" (unctad, 2024, p. 10) The Intergovernmental Panel on Climate Change (IPCC) recognizes the promising role of digital technologies—including sensors, the Internet of Things (IoT), and artificial intelligence (AI)—in mitigating climate change impacts, optimizing energy management, boosting consumption efficiency, and encouraging the uptake of low-emissions technologies. (unctad, 2024, p. 10)

Thus, it can be stated that the net effects—representing the difference between the direct and indirect impacts of digital transformation—can lead to a significant overall reduction in greenhouse gas emissions. According to the Global e-Sustainability Initiative (GeSI), the ICT industry's sustainability association, ICT applications could avoid up to 20% of global annual GHG emissions by 2030 (indirect effect), while the ICT sector itself causes approximately 2% of global GHG emissions. (. Bieser & Hilty, 2018, p. 2)

This study aims to examine the impact of digital transformation on environmental sustainability to derive practical recommendations for enhancing environmental sustainability in Arab countries through digital technologies. It addresses the main research question: To what extent does digital transformation contribute to environmental sustainability in Arab countries? The study covers the theoretical background, hypothesis development, methodology and analytical tools, appropriate diagnostic tests, short- and long-run model estimation, followed by results and recommendations.

2. Background and hypotheses

The Arab World is taking serious steps towards digital transformation and the integration of the digital economy. (Arab Economic Unity Council, 2018, p. 11) ; however, progress varies from country to country. Many Arab governments have adopted ambitious digital transformation strategies and launched initiatives in the areas of e-government and digital commerce, which has led to significant growth in e-services and technology start-ups. (Arab Federation for Digital Economy, 2025)

According to the Arab Digital Economy Index, Gulf countries lead digital growth, occupying the top positions with scores ranging from 59 points for Oman to 75 points for the UAE. (The Arab Federation for the Digital Economy, 2024, p. 36) The UAE and Saudi Arabia secured first and second places respectively in this ranking. This aligns with IMD digital competitiveness rankings and the ITU's IDI index, (World Competitiveness, 2025, p. 33) where these nations hold advanced global positions due to investments in digital infrastructure and AI. Following the Gulf countries, the second group emerges as the active nations in digital transformation, comprising Jordan, Morocco, Tunisia, Egypt, Algeria, and Lebanon, which achieved scores ranging from 44 points for Lebanon to 55 points for Jordan. Then came the third group, the aspiring development countries, which included Iraq, Syria, Djibouti, Mauritania, Sudan, Libya, Comoros, Somalia, Yemen, and Palestine, achieving scores ranging from 17 points for Palestine to 29 points for Mauritania on the scale of the Arab Digital Economy Index. the digital divide persists, with some lower-income or conflict-affected Arab countries lagging behind. Overall, the current trend is positive and on the right direction, with a growing recognition of the importance of the digital economy and its inclusion among development priorities.

Many Arab countries have adopted qualitative measures and strategies to facilitate the transition toward a digital economy by embracing digital technologies such as e-government, digital financial services, and smart energy management systems. These initiatives impact various sectors in Arab economies, including environmental sustainability, where digital transformation serves as a pivotal factor in enhancing sustainability by reducing carbon footprints and conserving natural resources—for instance, digital services reduce reliance on paper documents, thereby lowering tree harvesting and water consumption in production. Moreover, smart transportation and energy systems improve energy efficiency and curb greenhouse gas emissions, while remote education and work platforms minimize commuting, further decreasing emissions from traditional vehicles.

Several studies have examined the relationship between digital transformation and environmental sustainability, finding a positive relationship, such as the study by Yanni Song et al., which found that corporate digital transformation significantly contributes to reducing carbon emission intensity by enhancing corporate social responsibility and total factor productivity levels. The impact of corporate digital transformation on carbon emission intensity exhibits heterogeneity across highly polluting industries versus non-highly polluting industries, as well as between low-carbon pilot cities and non-pilot cities, with the carbon reduction effect being more pronounced in non-highly polluting industries and low-carbon pilot cities. This was determined after estimating a panel data model analyzing the digital transformation effects of Chinese listed companies from 2007 to 2022. (Yanni , Zijun, & Yingchun , 2025) Lin Guo et al.'s study, which examined the impact of digital transformation in focal firms on carbon emission intensity in upstream production and distribution firms within supply chains—particularly in the context of global low-carbon green development—concluded that digital transformation reduces carbon emission intensity by 9.97% in production firms and 11.9% in distribution firms. (Lin , Shanna , Ying , Chunyuan , & Bin , 2025)

According to the study by Yinlong Ma and Ruirui Li, the digital economy can promote environmentally sustainable energy practices through digitization, thereby contributing to Sustainable Development Goal 13 (Climate Action) by improving energy efficiency and supporting the transition to renewable energy. (Yinlong & Ruirui, 2025) Sanglin Zhao et al. examined the impact of digital transformation on carbon dioxide emissions through an econometric study of Chinese construction companies over the period 2000–2021, and found that digital transformation can significantly reduce firms' carbon emission intensity, mainly by promoting green technological innovation, improving total factor productivity, and optimizing production processes and business structures. (Sanglin , Hao , Jikang , & Måns , 2025) Marwa Kamal also concluded an inverse relationship between information and communication technology (ICT) and carbon dioxide emissions. This finding emerged from an empirical study employing the Autoregressive Distributed Lag (ARDL) approach over the period 2000-2023 in Egypt.) Kamal(2025 ، Therefore, our first hypothesis is as follows:

H1. There exists a significant positive long-run relationship between digital transformation and environmental sustainability in Arab countries.

Patents contribute to reducing carbon dioxide emissions through the development of green technologies and improved energy efficiency. Green technology plays a pivotal role in addressing major environmental challenges such as climate change, water scarcity, air pollution, and increasing waste. According to the World Economic Forum report, these technologies can contribute to reducing carbon emissions by up to 20% by 2030 if scaled globally. (WORLD ECONOMIC FORUM, 2025)

As climate change, pollution, and resource depletion intensify, green technologies emerge as vital solutions to mitigate the environmental impact of human activities. These innovations span key sectors, including renewable energy, waste management, sustainable transportation, energy efficiency, pollution control, sustainable manufacturing, and more. Through the transition to these technologies, carbon emissions can be significantly reduced, resource efficiency enhanced, and a cleaner, more sustainable planet supported. (Anuradha , 2025, p. 2225)

Green technologies provide practical solutions for reducing emissions, conserving resources, and limiting pollution, paving the way for a more sustainable and resilient future. This is confirmed by numerous studies, including the study by Yuhan Gong et al., which concluded that promoting green innovation and stimulating environmental entrepreneurship are the two primary mechanisms for reducing emissions in China. (Yuhan , Cao, & Yuan, 2024) Similarly, the study by Xinhui Lu et al. demonstrated that green technological innovation can significantly mitigate carbon emission intensity but cannot reduce it completely. (Lu & Lu, 2024) Qingfeng Cao et al. also investigated the contribution of artificial intelligence technology to reducing carbon dioxide emissions using data from 30 countries over the period 2005-2020. AI technology level was measured by the number of registered patents in each country, and the study results indicated that AI technology significantly reduces carbon emission levels. (Cao, Chi, & Shan, 2025) Sahli and Bousbaa also concluded, after conducting an empirical study analyzing the impact of digital transformation on environmental sustainability in Algeria during 1990-2023, that the effect of resident patent applications on the environmental sustainability index is negative and statistically significant. This indicates the importance of the registered patent applications variable in reducing carbon dioxide emissions in Algeria. (Lazhar & Bousbaa, 2025) Based on the aforementioned findings, the second hypothesis states :

H2. An increase in patents per million inhabitants reduces CO_2 emissions, indicating that technological innovation has a positive environmental impact.

The relationship between digital transformation and environmental sustainability can take the form of an inverted U-shape, extending the Environmental Kuznets Curve (EKC) theory. Originally, this theory posited that as per capita income increases, income inequality initially rises, but after a turning point, inequality begins to decline with further income growth, forming an inverted U-shaped or bell-shaped relationship between the two variables. (Kuznets , 1995, p. 3)Subsequently, this model was adapted to study the relationship between digital transformation and environmental sustainability, where digital transformation in its initial stage leads to increased carbon dioxide emissions due to direct energy consumption, but over time, its effect becomes positive for the environment through emission reductions, increased reliance on renewable energy, and promotion of green innovation.

Several studies have concluded an inverted U-shaped relationship where digital transformation initially increases CO2 emissions (rebound effect) and then decreases them at advanced digitalization levels. This is confirmed by the study of Ying Chen, which, using data from the China Family Panel Studies (CFPS) for the period 2014-2018, applied a fixed effects model to analyze the relationship between digital economy growth and households' indirect carbon emissions. The study concluded an inverted U-shaped relationship between the digital economy and households' indirect carbon emissions. Initially, households' indirect carbon emissions rise due to increased consumption of energy-intensive products, but as digital technologies mature, emissions decrease as a result of improved efficiency and sustainable consumption. (Ying , Donglin , Chenfeng , & Xiaochao , 2025) Mohamed El-Sayed Rady et al. also investigated the role of the digital economy in reducing carbon dioxide emissions as a proxy measure for achieving sustainable development in selected Arab countries. Using panel data from 13 Arab countries over the period 2005-2019, the study concluded that in the early stages of digitalization, the digital economy leads to increased carbon dioxide emissions. However, once digital economy development reaches a certain level, carbon dioxide emissions can be effectively mitigated, indicating an inverted U-shaped relationship between carbon dioxide emissions and the digital economy. (El-Sayed Rady, Mohamed Badr, & Abdel Hadi, 2023) There is another study by researcher Angel Melguizo and others that attempted to examine the relationship between artificial intelligence—as a form of digital transformation—

and the environment. The paper used new empirical evidence on the evolution of artificial intelligence and its environmental impacts in 23 middle- and high-income countries, confirming that initially, in most countries, artificial intelligence increases energy consumption and carbon dioxide emissions. Over time, it has a positive environmental impact by reducing emissions and increasing reliance on renewable energy—what is known as the 'green AI Kuznets curve'—and this turning point in direction is achieved when the artificial intelligence market ranges between \$220 and \$580 per capita. (Melguizo, , Katz , & Jung, 2025) Therefore, our third hypothesis will be as follows:

H.3 The impact of digital transformation on environmental sustainability is non-linear; in the early stages it increases carbon dioxide emissions, then reduces them after reaching a certain threshold level (inverted U-shape)

3. Research methods

3.1 Sample selection and data

To test the study's hypotheses and examine the impact of digital transformation on environmental sustainability, data from 14 Arab countries (Algeria, Tunisia, Morocco, Egypt, Jordan, Lebanon, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Iraq, Mauritania) out of the 22 Arab countries were collected over the period from 2005 to 2024. Initially, the study aimed to include all Arab countries, but due to the unavailability of essential data for the remaining countries, they were excluded.

This study uses panel data analysis, as it is the most appropriate because it takes into account the effect of time change and the effect of cross-country variation. In this study, the panel data are represented by combining a sample of 14countries (the cross-sectional dimension) over a period extending from 2005 to 2024 (the time dimension). Data processing and analysis were conducted using EViews 13 software.

The study relied on the extended STIRPAT model, which is an extension of the IPAT model. The IPAT model was first proposed by Ehrlich and Holdren (1971) as a framework for studying the impact of population growth on the environment. According to researchers, in an agricultural or technological society, each individual exerts a negative impact on their environment, as they participate in the use of renewable and non-renewable resources. (Ehrlich & Holdren, 1971, p. 1212)

The total negative impact of such a society on the environment can be expressed in its simplest form by the following equation: $I=P\cdot F$

where P is the population size, and F is a function that measures the per capita impact. With the advancement of the debate and empirical studies, the term F was decomposed into two main components: the level of affluence or per capita consumption (Affluence), denoted by A, and the level of technology used in production and consumption (Technology), denoted by T, so that the total impact became: $I=P\cdot A\cdot T$ (Chertow, 2008, p. 17)

Although the IPAT model and its variants provide valuable insights into the pathways through which human actions translate into environmental impacts, they suffer from significant theoretical limitations. Specifically, the IPAT framework assumes a strictly linear relationship among the variables, implying that a 1% increase in any of the right-hand-side factors will lead to a 1% increase in environmental impact. To overcome some of these limitations, Rosa and Dietz (1998) proposed the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology. (Vélez-Henao, Vivanco, & Hernández-Riveros, 2019)

This model was constructed by reformulating the IPAT identity into a stochastic specification: $I=aP^bA^cT^de$, where I, P, A, and T have the same interpretation as in the original IPAT equation; a, b, c, and d are parameters, and e is a residual term. In this new formulation, observed data on I, P, A, and T can be used to estimate a, b, c, d, and e using statistical regression methods. The reformulated version effectively converts the IPAT accounting identity into a general linear model, within which statistical techniques can be applied to test hypotheses and to evaluate the non-proportional contribution of each driving factor. (York, Rosa, & Dietz, 2003, p. 354)

This study employs an extended STIRPAT model for the variables affecting environmental sustainability, which retains the same basic framework of the STIRPAT approach but incorporates additional explanatory variables beyond population (P), affluence or living standards (A), and technology (T) by including a digital transformation variable, in a manner consistent with the focus of the research paper.

3.2 Variables

The first step in assessing the impact of digital transformation on environmental sustainability involves identifying the variables included in the model based on economic theory and prior studies. The following are the variables of the study:

The dependent variable is the one whose behavior we seek to explain, and the impact of a set of factors on it has not yet been determined. In this study, it represents environmental sustainability, which will be expressed as per capita carbon dioxide emissions obtained from the Our World in Data website.

The independent variables are those whose impact on environmental sustainability is to be determined. They have been identified in accordance with the extended STIRPAT model as previously mentioned, and Table 1 summarizes them as follows:

Table 1

Independent Variables of the Study

	Variable	Definition	Symbol	Source
A	GDP per capita	Each person's share in the country's gross domestic product is calculated by dividing the gross domestic product of a specific country by its population	GDP-PC	World Bank Database
P	Population	Total number of individuals residing in a specific geographic area	POP	World Bank Database
T	Resident patent applications	Number of patent applications filed by residents of the country (applicants residing in it) per million of its total population	Patents	WIPO Database

	per million population			
X	Digital Transformation	It will be expressed as the percentage of internet users, which is the percentage of the total population using the internet.	Internet	World Bank Database

Source: Prepared by the researcher

To facilitate estimation and hypothesis testing, logarithms will be applied to the statistical model's variables to transform them into elasticities, whereby each variable's coefficient interprets the percentage change in environmental sustainability resulting from a 1% increase in that variable.

4.Empirical results

4.1Descriptive statistics

Before commencing the analysis, hypothesis testing, and model estimation, it is essential to describe the data of the study variables and elucidate their main characteristics through descriptive statistical analysis methods, which are summarized in Table 2. As evident from the table below, the average carbon dioxide emissions for the 280 observations reached 12.58 tons per capita, while the average per capita GDP amounted to 25,657.10 US dollars. The average population was estimated at 20,410,051 individuals, and the average number of resident patent applications per million inhabitants for claimants stood at 7.57%. The average internet user penetration rate was 56.04%. Furthermore, Table 2 shows that the highest standard deviation was recorded for the population variable, indicating a high likelihood of dispersion of its values from the arithmetic mean. In contrast, per capita carbon dioxide emission values exhibit a relatively low standard deviation compared to other variables, signifying low dispersion and high homogeneity of carbon dioxide emissions. Regarding skewness coefficients, most were positive, implying that their statistical distribution is right-skewed, except for the internet user penetration rate series, which exhibited a negative skewness coefficient, indicating a left-skewed asymmetric distribution. Additionally, Table 2 reveals that the probability value corresponding to the Jarque-Bera statistic is below the 0.05 significance level, suggesting non-normality of the distribution, which aligns with the skewness coefficient results. Nevertheless, these findings do not affect the model's validity, given that the sample size exceeds thirty.

Table 2

Descriptive analysis of the study sample

	CO2	**GDP-PC**	**POP**	**Patents**	**Internet**
Mean	12.58	25657.10	20410051	7.57	56.04
Median	4.08	4915.50	8648474	4.00	57.00
Maximum	61.42	2408680	116538256	95.00	109.20
Minimum	0.49	1418.500	825408	0.00	1.00
Std.Dev	12.91	144170.2	25825673	13.11	31.92
Skewness	1.052	16.21	2.03	3.85	-0.11
Kurtosis	3.46	268.51	6.892	21.049	1.70

Jarque-Bera	54.26	834726.5	369.89	4495.575	20.12
Probability	0.00	0.00	0.00	0.00	0.000043
Sum	3524.10	7183989	5714814196	2122.00	15691.82
Sum Sq. Dev.	46500.60	5799024524848.806	1.860833387596626e+17	48004.27	284390.8
0bservations	280	280	280	280	280

Note. Source: Prepared by the researcher based on EViews 13 output dated December 19, 2025"

4.2Regressionanalysis–hypotheses 1 and 2

This regression analysis examines whether there exists a positive long-term relationship between digital transformation and environmental sustainability in Arab countries, concerning the first hypothesis. Additionally, as the second hypothesis tests whether an increase in the number of patent applications per million inhabitants reduces carbon dioxide emissions. As a preliminary step, stationarity tests for the study variables will be conducted. Unit root tests constitute an essential preliminary step for assessing the stationarity of the time series under study and determining their orders of integration. This procedure is critically important to ensure the validity of empirical results and prevent spurious regressions. This study employs commonly used panel unit root tests: Im, Pesaran, and Shin W-stat (IPS) and ADF-Fisher Chi-square test. Table 3 presents these results.

As evident from Table 3 below, per capita GDP and internet user penetration rate are stationary at their levels, as the probability values (p-values) for both the Im-Pesaran-Shin W statistic and the ADF-Fisher Chi-square test are below the 0.05 significance level. In contrast, per capita carbon dioxide emissions and the population series are non-stationary at their levels according to both the Im-Pesaran-Shin W statistic and the ADF-Fisher Chi-square test, as their corresponding p-values exceed the 0.05 significance threshold. However, after first differencing, the p-values for both tests fall below the 0.05 significance level, indicating that both series become stationary at first differences. Consequently, none of the study variables exhibit second-order integration, I(2), thereby satisfying the fundamental prerequisite for estimating the ARDL model for panel data, which requires all variables to be of order I(0) or I(1).

Table 3

Unit root tests for the stationarity of the study's variables using the Im, Pesaran and Shin W-stat (IPS) test and the ADF-Fisher Chi-square test

	Im, Pesaran and Shin W-stat	ADF - Fisher Chi-square

lCO2 (At the level)	-1.64487	**41.0134**
Prob	0.0500	**0.0536**
lCO2 (At the first difference)	-9.26244	**136.434**
Prob	0.0000	**0.0000**
LGDP-PC	-2.81393	**55.7360**
Prob	0.0024	**0.0014**
lPatents (At the level)	-0.82179	**43.2033**
Prob	0.2056	**0.0333**
lPatents (At the first difference)	-10.5748	**151.793**
Prob	0.0000	**0.0000**
lPOP	-3.77600	**74.5134**
Prob	0.0001	**0.0000**
lInternet	-7.15167	**134.868**
Prob	0.0000	**0.00000**

***Note.* Source: "Prepared by the researcher based on EViews 13 output dated December 19, 2025"**

Before estimating the long-run relationship between the study variables, the optimal lag period will be determined. Several statistical criteria are used to determine the optimal lag lengths, including Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (BIC), and Hannan-Quinn Criterion. In the model estimated in this study, the dependent variable representing environmental sustainability is CO2 emissions, while the independent explanatory variables are internet users' ratio, GDP per capita, population size, and resident patent applications per million inhabitants. According to the Akaike criterion, which yields the lowest value and is automatically determined by the EViews 13 statistical software, the values 1,0,1,0,0 indicate the optimal lag lengths for the study's variables.

Following the investigation of the integration orders of the variables—which reveal a mix of I(0) and I(1)—and the determination of the optimal lag lengths, the Panel ARDL model will now be estimated using the MG and PMG approaches. And Table 4 illustrates these results.

Table 4

MG, PMG estimation results

Variables	**PMG**		**MG**	
	Long Run	Prob	Long Run	Prob
LInternet	-0.0105	0.0304	0.0078	0.808
LGDP-PC	-0.0009	0.7076	0.136	0.364
LPOP	0.0032	0.0036	-0.066	0.381
LPatents	-0.02	0.9940	0.0059	0.480
Short Run				
COINTEQ	-1.090	0.0000	-1.196	0.0000
D(LGDP-PC)	0.428	0.0029	0.457	0.0001

***Note*. Source : "Prepared by the researcher based on EViews 13 output dated December 19, 2025.**

Following the estimation of the Panel ARDL model using MG and PMG approaches, we now proceed to the Hausman test for model selection. And Table 5 shows that the test confirms the preference for PMG (χ^2 = 1.634, df = 4, p = 0.803), supporting long-run homogeneity across the 14 Arab countries.

Table 5

Hausman Test

Trade-off	**Statistics**	**DOF**	**P-Value**
MG/PMG	1,634	4	0.8026

***Note*. Source: "Prepared by the researcher based on EViews 13 output dated December 19, 2025**

As evident from Table 4, digital transformation, expressed by the internet user penetration rate, has a significantly negative impact on environmental sustainability. This means that a 1% increase in internet users will lead to a 1.05% decrease in carbon dioxide emissions in the long run across 14 Arab countries. Both per capita GDP (LGDP = -0.0009, t = -0.376) and patent applications per million inhabitants (LPATENTS = -0.00002, t = -0.007) exhibit an inverse relationship with environmental sustainability, although these effects are statistically insignificant.

Table 4 further reveals that a 1% increase in population (LPOP = 0.0032, t = 2.76) results in a 0.32% increase in CO2 emissions, confirming a significant positive relationship between population growth and carbon emissions in the long run across the 14 Arab countries.

The table reveals that the error correction term (ECT) equals -1.090 (p = 0.0000), which is negative and statistically significant at the 1% level. This confirms cointegration among the model variables and indicates that 109% of the disequilibrium is corrected within one year, demonstrating a robust return-to-equilibrium mechanism across the 14 Arab countries.

In the short run, Δln(GDP) exhibits a positive and significant coefficient (0.428, p=0.0029), implying that a 1% increase in per capita GDP leads to a 42.8% rise in CO2 emissions. Conversely, in the long run, per capita GDP shows no significant effect (LGDP = -0.0009, t = -0.376), indicating that while economic expansion generates immediate emissions through fossil fuel dependence, this impact dissipates over time, potentially due to digital transformation (LINTERNET = -0.0105)

4.3 Regression analysis– hypotheses 3

To clarify whether the relationship between digital transformation and environmental sustainability follows an inverted U-shape, three main approaches will be employed, based on data characteristics and model assumptions:

- Pooled Ordinary Least Squares (OLS) method: Assumes that coefficients and intercepts are constant across all cross-sectional and time units; i.e., all individuals, countries, or firms are treated as a single sample.

- Fixed Effects model: This model allows intercepts to vary across units (individuals, countries, etc.) while assuming constant coefficients.

- Random Effects model: This model assumes that differences between cross-sectional units arise from random factors uncorrelated with the independent variables.

Table 6 summarizes the results of these three models.

Table 6

Panel model coefficient estimation results:

	Estimation method					
	The Pooled OLS Regression Model	Prob	The Fixed Effects Regression Model	Prob	The Random Effects Regression Model	Prob
C	-7.563	0.000	10.414	0.000	8.602	0.000
LN_Digital_sq	-0.027	0.085	-0.015	0.0015	-0.018	0.0002
linternet	0.157	0.077	0.231	0.000	0.235	0.000
lgdp	0.998	0.000	0.027	0.168	0.097	0.000
lpop	0.005	0.840	-0.588	0.000	-0.513	0.000
lpatents	0.027	0.270	0.028	0.0002	0.027	0.0002
F-Statistic	496.34		2310.292		43.374	
Prob	0.000		0.000		0.000	

***Note*. Source: "Prepared by the researcher based on EViews 13 output dated January 7, 2026**

After estimating the three models, they are compared, and the most appropriate model is selected based on two tests. The Lagrange Multiplier test is used to differentiate between the Pooled Ordinary Least Squares model and the Random Effects model, which determines whether there are significant unobserved differences between the study sample units (countries) that substantially affect the dependent variable. The null hypothesis states that differences between units are statistically insignificant (no random effects exist), and that the data are suitable for the Pooled OLS model. The alternative hypothesis states that there are substantial differences between countries, making the Random Effects model more appropriate. The results of this test are presented in the table below. As shown in Table 7, the probability value corresponding to the test is less than 5%, indicating rejection of the null hypothesis and acceptance of the alternative hypothesis, which suggests the presence of statistically significant differences between the countries in the study sample. Consequently, we conclude that the Random Effects model is the most appropriate for estimating the relationship.

Table 7

Lagrange multiplier test:

	Cross-section	Time	Both
Breusch - Pagan	260.6200	2.2673	262.887
Prob	0.0000	0.1321	0.0000

***Note*. Source: "Prepared by the researcher based on EViews 13 output dated January 7, 2026.**

We now proceed to select the optimal model between the Fixed Effects regression model and the Random Effects regression model. For this purpose, the Hausman test is employed. Table 8 presents the results of the Hausman test. According to the Hausman test:

Null Hypothesis (H_0): The Random Effects model is appropriate.
Alternative Hypothesis (H_1): The Fixed Effects model is appropriate

Based on the results of Table 8, we reject the null hypothesis and accept the alternative hypothesis. Therefore, the Fixed Effects model is appropriate, since the probability value (p) of the test is less than 0.05.

Table 8

Hausman test

Test Summary	Chi-Sq Statistic	Chi-Sq.df	Prob
Cross-section random	201.817	5	0.0000

***Note*. Source: "Prepared by the researcher based on EViews 13 output dated January 7, 2026.**

The Fixed Effects model reveals that the digital transformation coefficient is positive and significant, indicating that digital transformation in its initial stages increases carbon dioxide emissions by 23.1%. Additionally, the coefficient of the squared logarithm of digital transformation is negative and significant, suggesting a decline in carbon dioxide emissions in advanced stages, which provides evidence of improved environmental sustainability following a transitional phase. According to this model, the economic growth effect appears insignificant on environmental sustainability, population reduces carbon emissions, and innovation increases emissions.

5. Discussion

The estimation results of the Panel ARDL model for 14 Arab countries over the period 2005–2024 using the PMG estimator reveal the existence of a cointegrating relationship between carbon dioxide emissions and GDP per capita, population, resident patent applications per million inhabitants, and the share of internet users. The error correction term is negative and statistically significant, indicating a rapid adjustment of emissions back to their long-run equilibrium path. The long-run estimates further show that a 1% increase in internet penetration leads to a 1.05% reduction in carbon dioxide emissions, which can be attributed to investment in digitalization and green technologies. Digital transformation can reduce energy consumption through smart grids and artificial intelligence solutions, facilitating the integration of renewable energy, reducing dependence on fossil fuels, and supporting the transition to a low-carbon economy. Therefore, it can be concluded that digital transformation in Arab countries will reduce carbon emissions in the long-run, thus confirming the validity of the first hypothesis.

An increase of 1% in population growth in Arab countries leads to a 0.32% rise in carbon emissions. This is because higher population growth raises the demand for energy and resources, thereby intensifying environmental pressure.

The long-run results show that the coefficient of GDP per capita is negative and statistically insignificant, indicating that the income level does not exhibit a clear long-run effect on carbon dioxide emissions in the Arab countries under study. This may be due to the fact that the relationship between income and emissions takes a nonlinear form, consistent with the Environmental Kuznets Curve hypothesis.

Patent applications did not exhibit a significant long-run impact on carbon emissions. This is attributed to the use of total patents rather than focusing on green patents, due to the researcher's inability to obtain specific statistics for the latter. Additionally, patents require time to be converted into applied technology, compounded by significant variation across Arab countries, where GCC countries dominate oil-related patents. This refutes the validity of the second hypothesis.

At the short-run level, the error correction term (ECT) was found to be negative and statistically significant, indicating the existence of a cointegrating relationship between carbon dioxide emissions and the explanatory variables. The value of the error correction coefficient (−1.90) reflects a very rapid speed of adjustment in correcting deviations from the long-run equilibrium path. The results also show that changes in GDP per capita have a positive and significant effect on CO22 emissions, as a 1% increase in GDP per capita leads to an increase in emissions of about 0.428% in the short run. This indicates that short-run economic growth in Arab countries remains carbon-intensive in nature; that is, the expansion of economic activity depends directly on increased consumption of fossil energy (industry, transport, construction), which is quickly translated into higher emissions before any potential effects of energy efficiency improvements or long-run structural transformation can materialize.

It is evident that the Fixed Effects model is the most appropriate for this study, which reveals a non-linear inverted U-shaped relationship between digital transformation and carbon emissions in Arab countries. Digital transformation increases carbon dioxide emissions by 23.1% in its initial stages, then reduces them after a turning point at a digitalization level of 2200 users per 1000 inhabitants—meaning that once internet penetration exceeds 220%, environmental sustainability in Arab countries begins to improve. This improvement results from the adoption of green technologies, green innovation, renewable energy sources, and advanced technologies that work to reduce and mitigate carbon dioxide emissions.

Consequently, during the initial adoption phase, digital transformation leads to negative environmental impacts. However, once a certain threshold of digital transformation usage is reached, the effect becomes positive. This is demonstrated by the negative quadratic coefficient in the estimation of carbon dioxide emissions, thereby confirming the validity of the third hypothesis.

6. Conclusion

The world has witnessed a significant digital transformation that has yielded substantial economic benefits, accompanied by numerous impacts on the reality and trajectory of sustainable development, particularly environmental sustainability. On one hand, digital transformation is considered one of the key factors enabling and enhancing the development of sustainable environmental solutions in the current era. Digital solutions help reduce waste, increase the efficiency of natural resource utilization, and enable digital technologies to advance renewable energy development, expand its scope, and use it more effectively, thereby driving the economy toward greater efficiency. On the other hand, the use of digital technologies can increase demand for raw materials, water, and energy, as well as raise greenhouse gas emissions.

The Arab world, like the rest of the globe, has experienced a noticeable acceleration in the pace of digital transformation in recent years, driven by ambitious government efforts and private sector initiatives. Therefore, this study aims to examine the extent of the impact of digital transformation on environmental sustainability in a sample of Arab countries during the period 2005-2024. The study employed the ARDL model for panel data and concluded that there is a long-term relationship between digital transformation—represented by the percentage of internet users—and environmental sustainability, proxied by per capita carbon dioxide (CO2) emissions. Specifically, a 1% increase in the percentage of internet users leads to a 1.05% decrease in per capita CO2 emissions in the long-run. The study also found that a

1% increase in population results in a 0.32% rise in CO2 emissions, while the effects of economic growth and patents are insignificant on environmental sustainability in the long-run. However, economic growth has a significant short-run effect, whereby an increase in per capita GDP leads to a 42.8% rise in CO2 emissions.

Furthermore, the estimation of the fixed effects model reveals that the relationship between digital transformation and environmental sustainability takes the form of an inverted U-shape. This means that digital transformation in its initial stages leads to an increase in carbon dioxide (CO2) emissions due to heightened energy consumption. However, in advanced stages—when the percentage of internet users exceeds 220% in Arab countries—it results in a decrease in CO2 emissions, stemming from the application of technology in the environmental domain and transforming the environment into a source of sustainability and preservation for future generations.

Based on the results obtained, the following points are proposed:

- Putting in place global policies to enable a more circular digital economy and reduce the environmental impacts arising from digitalization.
- Developing green data centers that rely on energy efficiency and renewable energy, with the imposition of stringent conditions on electricity and water consumption.
- Developing the digital economy in Arab countries to reduce the time spent in the "triple" phase (initial stages of digital transformation) and lower the carbon dioxide emissions it causes, while leveraging digital solutions to minimize its environmental impact.
- The importance of harnessing desert areas—which account for more than 90% of the land area in several Arab countries—in reducing reliance on fossil fuels and supporting green digital transformation by powering data centers with clean energy, thereby enhancing sustainability during the initial stages of digitalization.
- Employing digital tools such as artificial intelligence and the Internet of Things for managing resources, energy, and sustainable agriculture, thereby reducing waste and improving efficiency.
- Encouraging startups in the green economy and establishing a supportive legal and regulatory framework for them to enhance environmental innovation in Arab countries.

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