

Article

Digitalization and Carbon Footprint: Does ICT Reduce Carbon Footprint?

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Abstract: The potential economic and social benefits of digitalization are far-reaching and frequently discussed in public discourse. It is often portrayed as a silver bullet for addressing the world's increasingly urgent environmental challenges. In particular, digitalization is considered a key enabler of a low-carbon economy. However, realizing these technological potentials requires effective implementation in sectors with the greatest capacity for smart solutions—namely, transportation, buildings, and energy—to reduce the carbon footprint. Conversely, digital technologies can also contribute to an increased carbon footprint due to the complexities involved in constructing and maintaining digital infrastructures, as well as rebound effects. Therefore, the impact of digitalization on the carbon footprint is a subject of particular interest. This paper examines the effect of digitalization on the carbon footprint in the MENA region during the period from 2000 to 2022. The Generalized Method of Moments (GMM), Fully Modified Ordinary Least Squares (FMOLS) and the Dumitrescu-Hurlin causality test are employed for this analysis. The GMM results indicate that information and communication technology (ICT) has no significant impact on the carbon footprint in the short run. In contrast, the FMOLS results show that ICT is negatively associated with the carbon footprint in the long run. The causality test indicates robust evidence of unidirectional causality running from ICT to Carbon footprint in the MENA region, asserting the long-run estimation results.

Keywords: Digitalization; Carbon Footprint; GMM; FMOLS

1. Introduction

Digitalization's potential economic and social benefits are far-reaching and are addressed in public discourse. It is often envisioned as a silver bullet to mitigate—the world's increasingly urgent environmental issues, in particular, it is an important possible enabler for a low-carbon economy in the world [1,2]. However, the existing technological potentials should be correctly exploited by taking effective actions in the sectors which have the highest potential for smart solutions (i.e., transportation, building and energy sectors) to mitigate carbon footprint. On the contrary, digital technologies could increase carbon footprint due to the difficulties of the construction and maintenance of complex digital infrastructures and rebound effects. Hence the effect of digitalization on carbon footprint is a topic of special interest.

Despite the ubiquitous appearance of both digitalization and carbon footprint, there seems to be no clear

definition of carbon footprint and there is confusion what it actually means and measures. Many authors used carbon footprint as a synonym for emissions of all greenhouse gases, including carbon dioxide, expressed in CO₂ equivalents [3,4]. Others used the term as synonym for carbon dioxide emissions only [5]. The study uses the carbon footprint as a synonym for carbon dioxide emissions only that is caused by any activity directly and indirectly. This is due to many reasons: First, Other substances that have greenhouse warming potential are not based on carbon or are difficult to quantify due to data availability. Second, Methane could be included with carbon dioxide, but there is no extra information gained from a partially aggregated indicator that includes just two greenhouse gases [5].

MENA (Middle East and North Africa) region is characterized by a growing carbon footprint due to its dependence on producing and exporting hydrocarbon resources but it has a potential role in reducing carbon emissions [6]. At the same time, many countries in the MENA region are on their way to be leaders of digital transformation globally according to the networked readiness index as digital transformation might help these countries in mitigating carbon emissions and achieving environmental sustainability. Accordingly, it is crucial for the MENA region policymakers to give attention to the effect of ICT on carbon emissions [7]. However, there are many challenges that face digitalization in the region like infrastructural conditions required for them, security and privacy risks, lack of digital literacy, lack of awareness of the relevance of digital government in the public sector and society and lack of political support. These challenges might hinder policymakers from achieving their objective of using digitalization to mitigate carbon emissions and achieve sustainable development and environmental sustainability [7–9].

Among the first countries that made their way successfully for the digital transformation in the region are United Arab Emirates and Egypt. They have succeeded in providing advanced government services to the public, and they have exerted great efforts in adopting modern technology and catching up with the latest trends in all its sectors since 2001. Egypt also put ICT application on its national agenda as an enabler for socio-economic development in different sectors in the late 1990s. In addition, Egypt has witnessed several initiatives in ICT application in the economy such as PC for Every Home Initiative and E-government Initiative to increase the usage of new technologies [10]. However, both countries have recorded high and increasing carbon dioxide emissions over the last two decades [11].

In this regard, very few comprehensive studies investigated the effect of digitalization on carbon footprint and the proposed study is regarded as a first attempt to investigate this effect in the MENA region.

1.1. Importance of the Study

As the amount of carbon dioxide emissions from energy consumption is increasing heavily in the MENA region, the governments of different countries in the region have worked to reduce carbon emissions as a prerequisite for environmental sustainability [12]. Hence, many countries in the region adopted digitalization due to its great hopes in reducing carbon emissions. As a result, the study will investigate the effect of digitalization on carbon footprint in the region to provide new insights regarding this issue to policymakers [13]. In addition, as many countries in the region face challenges in ICT application, the study seeks to highlight these challenges and how they can be addressed—with specific focus on United Arab Emirates and Egypt—in order to ease the role of digitalization in mitigating carbon emissions and achieving environmental sustainability.

1.2. Research Objectives

The main objective of the proposed study is to study the effect of digitalization on carbon footprint in the MENA region and to address the challenges that face digitalization in the region with specific focus on United Arab Emirates and Egypt. Hence the study tries to answer the following questions to reach its objectives:

- 1) What is the role of digitalization in reducing carbon footprint in economic theory?
- 2) What is the role of digitalization in reducing carbon footprint in the United Arab Emirates and Egypt?
- 3) What are the challenges that face ICT application in the region? How can these challenges be addressed?
- 4) What is the effect of digitalization on carbon footprint in the MENA region (2000–2021)?

2. Literature Review

2.1. Background About Digitalization and Carbon Footprint in the MENA Region

2.1.1. Digitalization Concept

In academic literature, the terms “digitization” and “digitalization” are distinct concepts, though they are sometimes used interchangeably, leading to confusion. The first contemporary use of the term “digitalization” in conjunction with computerization appeared in a 1971 essay first published in the *North American Review*.

Digitization refers to the technical process of converting analog information into digital form. Brennen and Kreiss (2016) defined digitalization as “the material process of converting analog streams of information into digital bits”. This involves transforming physical or analog data, such as paper documents, photographs, or analog signals, into a digital format that can be processed, stored, and transmitted by computers. For example, scanning a paper document to create a PDF or converting records into MP3 files are instances of digitization.

Digitalization involves the integration of digital technologies into various aspects of our lives, including business, education, healthcare, and more. It has the potential to impact numerous aspects of our lives, including how we work, communicate, and consume goods and services, and access information [1]. Brennen and Kreiss (2016) described digitalization as “the way many domains of social life are restructured around digital communication and media infrastructures”. For example, digitalization has enabled remote work and online collaboration, allowing people to work and communicate from anywhere in the world. It has also enabled new forms of e-commerce, such as online shopping and digital payments, which have transformed the way we buy and sell goods and services.

The term “digitalization” can encompass a wide range of technologies, including artificial intelligence, machine learning, the Internet of Things (IoT), cloud computing, blockchain, and more. These technologies can be used to collect and process large amounts of data, automate tasks, and enable new forms of communication and collaboration [1].

In summary, digitization focuses on the conversion of analog data into digital form, while digitalization involves the broader integration and application of digital technologies leading to transformative changes in various sectors of society.

2.1.2. An Overview about Digitalization in the MENA Region

Technological trends related to digitalization and information and communications technologies (ICT) in the MENA region vary significantly due to differing levels of development both across and within countries. Numerous studies have indicated that many nations in the Middle East and North Africa, along with various societal groups within them, are not sufficiently prepared to harness new technologies for developmental progress. Additionally, the region often lacks strong governance structures to support innovation and ICT. Despite these challenges, nearly all MENA countries are implementing policies to promote digitalization as a means of advancing development. They are also opening the door for external influences—both indirectly, through mechanisms such as market competition, and directly, through the involvement of multinational corporations (like Google, Samsung, and Facebook) or global organizations (such as the World Bank, United Nations, Food and Agriculture Organization, and European Union) [8].

ICT development is affected by different forces (i.e., economic factors, technological advancement, political and legal frameworks, environmental considerations, globalization and education and workforce development) and it has major economic and societal implications for each country. To assess the state of each country concerning digital trends and their economic and societal implications, the Network Readiness Index is utilized. The Network Readiness Index (NRI) aims to highlight and examine key digital trends, uncover the main drivers shaping advancements in media, information, and communication technologies, and assess their broader societal impacts. Additionally, it provides practical recommendations to guide policymaking and implementation. **Figure 1** illustrates the NRI scores of MENA countries for the year 2023 [14].

The NRI 2023 framework retains its core structure based on four key pillars: Technology, People, Governance, and Impact. The Technology pillar focuses on assessing the quality and availability of technological infrastructure necessary for a country’s participation in the global digital economy. The People pillar examines how ICT is utilized across three main domains: individuals, businesses, and government institutions. The Governance pillar highlights the development and accessibility of policies and frameworks that support a dynamic and inclusive networked economy. Lastly, the Impact pillar measures the broad effects of digital engagement on economic and social outcomes.

Table 1 presents the overall NRI scores along with the scores for each of the four pillars for selected MENA countries.

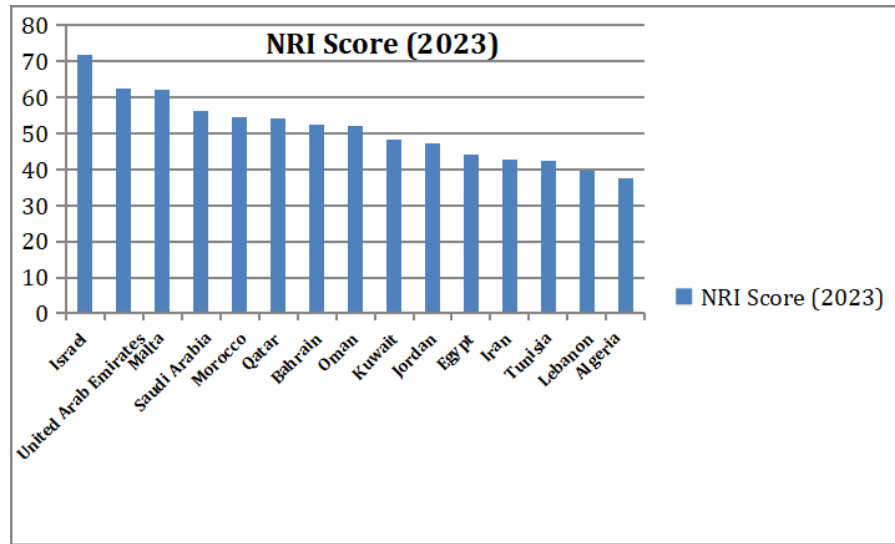


Figure 1. NRI Index for Selected MENA Countries.

Table 1. The NRI and Its Four Pillars Score for Selected MENA Countries.

Country	NRI Score (2023)	Technology	People	Governance	Impact
Israel	71.82	59.03	74.78	77.37	76.12
United Arab Emirates	62.43	56.61	62.2	66.63	64.26
Malta	61.94	49.71	57.05	73.95	67.04
Saudi Arabia	56.14	49.52	55.02	65.69	54.34
Morocco	54.43	39.2	41.59	50.46	50.47
Qatar	54.15	49.59	43.51	69.18	54.31
Bahrain	52.48	43.9	45.18	63.45	57.41
Oman	52.1	41.31	46.48	67.48	53.11
Kuwait	48.36	43.14	42.27	54.17	53.86
Jordan	47.29	40.05	49.19	55.16	44.75
Egypt	44.07	39.94	35.37	50.25	50.73
Iran	42.83	38.86	39.99	51.58	40.91
Tunisia	42.25	38.29	39.89	48.72	42.11
Lebanon	39.7	37.43	48.08	37.11	36.16
Algeria	37.52	31.45	35.63	41.18	41.82

2.1.3. Carbon Footprint in the MENA Region

Recent advancements in climate and environmental science have emphasized the need to understand carbon emissions not only in aggregate but also across spatial scales. According to Zhu et al. (2023), global carbon accounting systems suffer from inconsistencies in data coverage and resolution. Their study argues for a more unified global framework that integrates satellite data, national inventories, and bottom-up measurements. This macro-level perspective helps to identify broad patterns in carbon emissions and offers guidance for international climate agreements and cross-border mitigation strategies [15].

Moving to a regional context, Wang and Zhou (2018) focus specifically on East Asia, a region characterized by rapid industrialization and urbanization. Using a combination of spatial econometric techniques and land use data, their study demonstrates that regional emission patterns are significantly influenced by population density, transportation infrastructure, and energy policy choices. They advocate for region-specific interventions that align with broader global targets but are tailored to local realities [16].

At a more granular scale, Lee et al. (2020) present a city-level study that uses high-resolution spatial data to evaluate emission hotspots in urban environments. Their methodology incorporates land-use classification and point-source pollution data, showing that carbon intensity is often concentrated in areas with mixed residential-

industrial use. This local insight is crucial for city planners and environmental policymakers who aim to implement neighborhood-specific strategies [17].

Finally, Chen et al. (2024) integrate machine learning with spatial econometrics to map urban CO₂ emissions across Chinese cities [18]. Their model accounts for socio-economic, technological, and spatial heterogeneities, providing policymakers with predictive tools for emission forecasting. The authors highlight the growing potential of artificial intelligence in environmental monitoring, especially in fast-changing urban landscapes. Together, these studies offer a robust multi-level framework for understanding carbon emissions. They demonstrate that effective climate action requires not only global coordination but also regional specificity and local precision—each supported by appropriate digital technologies and data integration strategies [18].

The concept of the carbon footprint is extensively referenced in academic literature to denote the total volume of greenhouse gas (GHG) emissions generated—either directly or indirectly—by individuals, organizations, events, or products. These emissions are typically quantified in terms of carbon dioxide equivalents (CO₂e) [5]. Several methodological frameworks exist for measuring carbon footprints, the most common being production-based, consumption-based, and life-cycle assessment (LCA) approaches.

The production-based method calculates all GHG emissions produced within a defined geographic boundary, such as a country or region. It encompasses emissions from domestic industrial processes, energy generation, and transportation, but excludes emissions associated with imported goods. In contrast, the consumption-based approach shifts the focus to the end user by allocating emissions embedded in imported products to the consumer, while excluding those linked to exports [19]. Meanwhile, the LCA approach provides a comprehensive assessment by estimating emissions throughout the entire life cycle of a product, from the extraction of raw materials to its disposal or designated endpoint [20].

Rapid development and population growth in MENA countries have led to increased consumption of fossil fuels, water, and other non-renewable natural resources, which burden the environment. Although MENA countries have significantly contributed to carbon dioxide emissions, they have taken positive steps in the last decade to solve the main environmental problems and improve sustainability in their countries [21].

Figure 2 depicts carbon dioxide emissions in kilotons selected MENA (Middle East and North Africa) countries between 2000 and 2020. The figure shows that most MENA countries show a steady increase in carbon emissions, with Iran, Saudi Arabia, and Egypt being the top three carbon emitters in the region due to their heavy reliance on fossil fuels, their rapid growth, urbanization, and energy-intensive industries [21]. On the other hand, Yemen and Malta are the lowest carbon emitters in the region due to their small population size, limited industrialization, and slow economic growth [21,22].

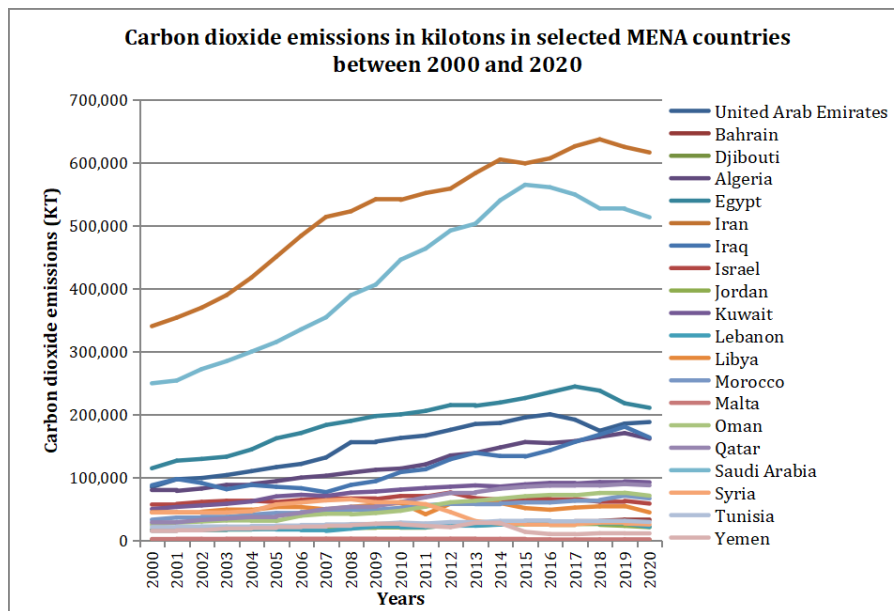


Figure 2. Carbon Dioxide Emissions in Selected MENA Countries Between 2000 and 2020.

Based on the previous information about environmental sustainability in the region, most MENA countries should invest in a number of energy efficiency and renewable energy schemes to reduce carbon emissions. In this theme, countries such as the UAE, Saudi Arabia, Kuwait, and Qatar aim to achieve 30, 15, and 20 percent, respectively, of their power generation from renewable energy sources by 2030. In addition, governments, non-governmental organizations, and industry experts in the region should invest their time and energy in building the institutions and regulations that aim at developing environmental education, awareness, and behavior change, and implementing waste management projects such as the introduction of the Green Building Regulations and the recycling strategies that preserve natural resources, reduce the carbon footprint and foster sustainability in this region [21]. It is worth mentioning that the role of digitalization is crucial in achieving all these techniques, as will be shown in the next point.

2.2. Theoretical Literature Review

The literature offers varying viewpoints on the environmental impacts of digitalization. Broadly, theoretical discussions on the relationship between ICTs and the environment can be grouped into two main categories: optimistic and pessimistic. The optimistic perspective views technological advancement and modernization as effective tools for addressing environmental challenges, particularly in reducing carbon emissions. In contrast, the pessimistic perspective expresses skepticism about the ability of technological innovation alone to prevent environmental degradation, suggesting that without broader systemic changes, such advancements may fall short.

2.2.1. Optimistic Perspectives

To begin the section on optimistic perspectives, different theories and reports on the relationship between CO₂ and ICTs will be reviewed.

(1) Ecological Modernization Theory

Ecological Modernization Theory (EMT) emerged in the 1980s through the work of German scholars such as Martin Jänicke and Josef Huber, and gained wider academic recognition in the 1990s through the contributions of Dutch sociologists Gert Spaargaren and Arthur Mol [23]. EMT provides a sociological lens to analyze how modern industrial societies attempt to reconcile economic development with environmental protection. It argues that modernization—encompassing industrialization, urbanization, globalization, and technological advancement—can evolve to incorporate environmental considerations into the core institutions of modernity, such as science, the market, and the state.

Contrary to earlier theories that viewed modernization as the root cause of ecological degradation, EMT proposes that modernization can become a solution if it integrates ecological rationality alongside economic rationality. In this context, institutional reforms, market mechanisms, and technological innovation are considered central vehicles for sustainability transitions. Spaargaren and Mol emphasized that institutions must evolve in ecologically informed ways to ensure long-term environmental integrity [24].

A critical application of EMT to the current study lies in its emphasis on the role of technological systems, particularly information and communication technologies (ICTs), in enabling environmental reform. Weak ecological modernization theorists highlight the use of technology to increase environmental efficiency, while strong theorists advocate broader systemic and political reforms toward ecological governance [25,26]. In both strands, ICTs are seen as instrumental—either by optimizing energy use, enabling real-time carbon monitoring (e.g., via IoT), or enhancing environmental transparency and policy responsiveness [27].

However, EMT has faced criticism. Some scholars question its reliance on qualitative or case-based methodologies and its occasional neglect of broader structural and systemic inequalities. Others argue that EMT overly generalizes from a small number of successful industry-specific cases—such as the Dutch chemical sector or the Thai pulp and paper industry—without sufficiently accounting for variations across sectors and geopolitical contexts [24,28]. Furthermore, assumptions that institutional changes inherently lead to environmental improvements require empirical validation, particularly regarding their effectiveness in reducing carbon emissions on a national or global scale [24,29].

Despite these critiques, EMT remains a valuable framework for understanding the potential role of digital transformation in achieving environmental goals. By embedding environmental logic into technological and institutional innovation—especially within smart cities and sustainable ICT infrastructures—the theory supports a

pathway where modernization and decarbonization are not mutually exclusive but mutually reinforcing.

(2) Environmental Kuznets Curve

Kuznets (1955) proposed that the relationship between income per capita and income inequality follows an inverted-U shape: inequality tends to rise in the early stages of economic growth, but eventually declines as development progresses. This concept was later extended to environmental issues in the early 1990s, when Grossman and Krueger applied it in their study on the environmental impacts of the North American Free Trade Agreement [30]. This adaptation, known as the Environmental Kuznets Curve (EKC), suggests a similar inverted-U-shaped relationship between environmental degradation and income per capita. According to the EKC hypothesis, environmental harm initially worsens with rising income, but after reaching a certain income threshold—the turning point—it begins to improve as higher-income societies invest more in environmental protection [31]. **Figure 3** illustrates this relationship.

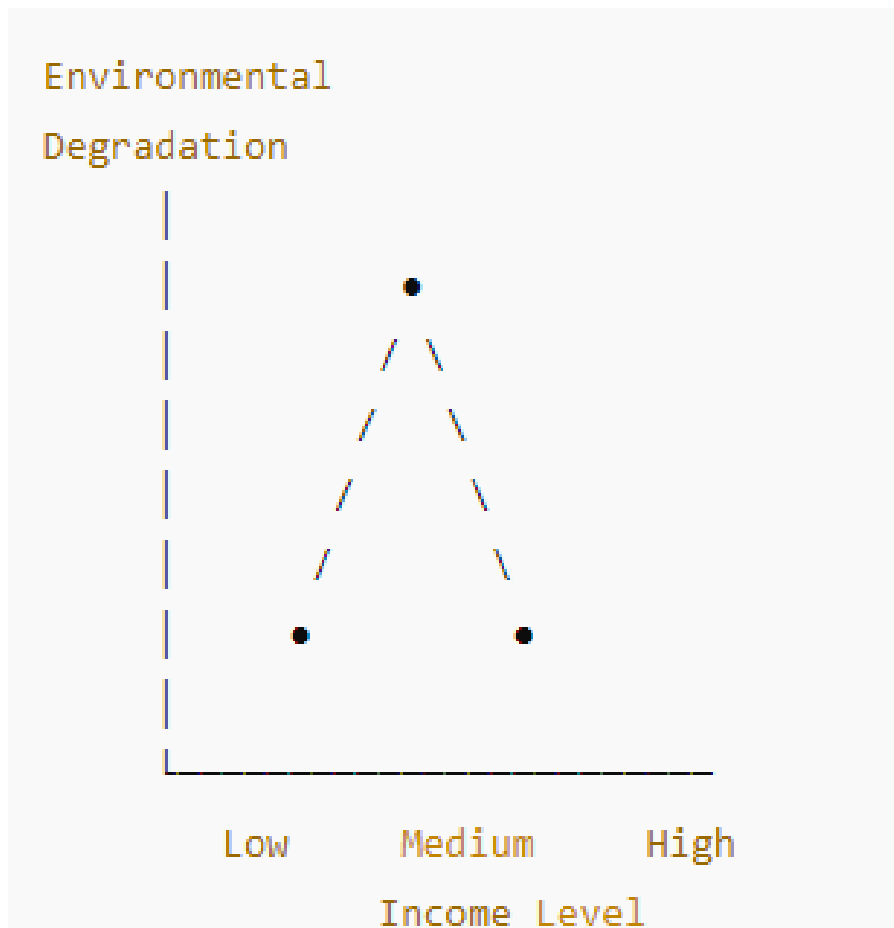


Figure 3. Environmental Kuznets Curve.

It is also important to note that in discussions surrounding environmental degradation and ICT development, many scholars extend the Environmental Kuznets Curve (EKC) framework to focus on ICT rather than purely economic growth. For instance, Kuhndt et al. (2003) included a figure in their report (**Figure 4**) that illustrates the potential environmental impacts of ICT development over time [32]. The figure suggests that, prior to the emergence of the “Digital Society,” human welfare and the use of natural resources were closely linked. However, in the era of the Digital Society, this relationship changes—human welfare continues to improve while the reliance on natural resources declines. ICTs are portrayed as the driving force behind this decoupling, playing a dual role by enhancing human welfare and decreasing environmental pressures. Although the figure is not explicitly labeled as an EKC, the inverted U-shaped trajectory it depicts aligns with the classic EKC hypothesis [32].

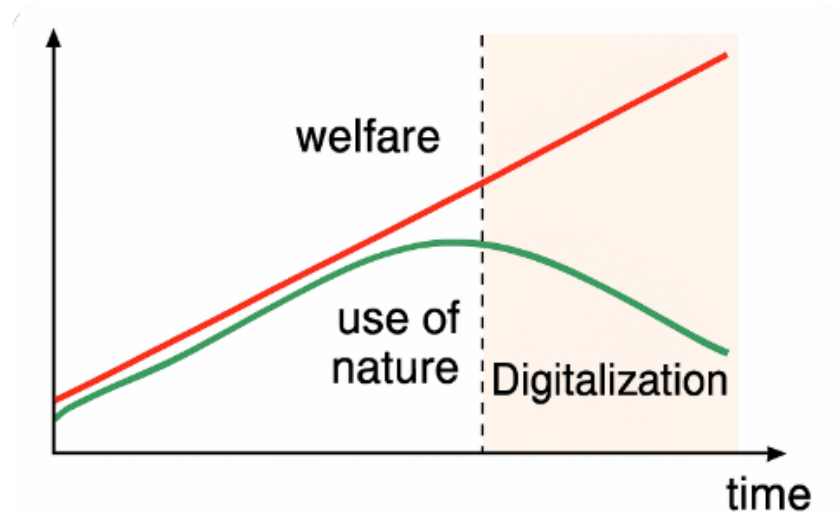


Figure 4. Potential Contribution of ICTs to Decoupling ‘Welfare’ From the Use of Natural Resources.

The Environmental Kuznets curve could be criticized due to conceptual and methodological reasons. The conceptual one is that the shape of the EKC changes due to the multiplicity of the factors that affect the economy–environment relationship [33]. The methodological one is that the EKC relation is not robust empirically [30].

(3) Technological and Environmental Leapfrogging

Leapfrogging refers to a development strategy whereby developing countries bypass environmentally harmful stages of economic growth by adopting advanced, resource-efficient, and cleaner technologies. Rather than following the historical path of industrialized nations—relying on pollution-heavy, hydrocarbon-based systems—developing nations can “leapfrog” directly to more sustainable, modern technologies [34].

This approach contrasts with the Environmental Kuznets Curve (EKC) framework. While the EKC implies that countries must first undergo phases of industrial pollution before reaching a “turning point” where cleaner technology becomes viable, leapfrogging allows less-developed economies to adopt those cleaner, more efficient technologies early on—without experiencing the environmentally destructive stages [35].

There are two types of leapfrogging:

- **Skipping generations of technology** – This occurs when countries bypass older technologies entirely. A notable example is China’s transition directly from limited communication infrastructure to widespread use of wireless networks, effectively skipping the wired telephone phase.
- **Leaping to become a technological leader** – This involves not just adopting modern technologies but also surpassing global leaders. A case in point is the Korean steel industry, which not only caught up with leading producers but also advanced to the forefront of technological innovation in the field [36].

Perkin (2003) illustrated that Leapfrogging existing approaches maintain that achieving goals of leapfrogging (i.e., reducing the environmental burden of the industrialization phase) requires five conditions to be met: First, a shift towards “clean” technologies instead of end of-pipe (EOP) technologies [33]. Second, investing in clean plant and equipment at an early stage of industrialization path in developing countries [29]. Third, large-scale transfer of clean technology from developed economies to developing ones [34]. Forth, strengthening incentives by the government for the uptake of clean technologies such as introducing strong legislative frameworks for environmental protection and economic policy reform, including the privatization of state-owned enterprises, trade and investment liberalization and the removal of so-called perverse subsidies (for water, energy, etc.) [34,37]. Finally, International assistance from developed economies to support financing for clean technologies since the high capital costs often discourage adoption [38,39].

Existing approaches of leapfrogging could be criticized on three grounds: First, very little has been said about specific pollutants or resources that need to be prioritized and specific environmental targets that need to be

reached. This ambiguity entails problems public policy agenda setting. Second, the assumption that clean technologies are sufficient to enable leapfrogging in developing economies is challenged by the suitability of these technologies to the requirements of users in developing economies and the low price of EOP technology which are substitute to clean technology [34,40]. Third, existing approaches of leapfrogging assume that the only requirement for innovation and leapfrog technologies diffusion are strong incentives directed to less environmentally damaging production. However, incentives must be complemented by a range of capabilities which are needed by firms to respond to these incentives [34,39,41].

2.2.2. Pessimistic Perspective

While optimistic perspectives find encouraging trends in technological solutions proving their success through singular cases, pessimists see a much different picture and consider the global system in its entirety [35].

(1) Political Economy: World Systems Theory, Treadmill of Production Theory and the Jevons's Paradox

World Systems Theory (WST), developed by Immanuel Wallerstein, offers a political-economic framework that explains global economic inequality by analyzing the world system as a whole rather than focusing on individual nations [34]. According to this theory, the global economy comprises interdependent regions that rely on each other for essential resources such as food, raw materials, energy, and security [42].

Wallerstein (1974) emphasizes that the global market operates through a multicultural, territorial division of labor. This structure involves the production and exchange of fundamental goods and resources essential for daily life. World Systems Theory divides the global economy into three interrelated regions based on economic roles and power dynamics: core, periphery, and semi-periphery. Core regions dominate with advanced technology, capital-intensive production, and strong institutions. Periphery regions focus on labor-intensive industries and raw material exports, often with weaker infrastructure and economic dependence. Semi-periphery regions blend characteristics of both, acting as intermediaries. This structure highlights and sustains global economic inequality.

This global structure perpetuates unequal exchange, wherein dominant, wealthy core countries exploit peripheral regions by extracting surplus value and resources. This exploitation reinforces disparities in wealth and development [35].

A more recent extension of WST is the theory of ecological unequal exchange. This perspective argues that wealthier nations maintain their environmental quality by effectively outsourcing environmental degradation to poorer nations. Developing countries often carry an ecological deficit, exporting resource-intensive and polluting goods, thereby allowing developed countries to avoid the environmental consequences of such industries within their own borders [43]. Therefore, a nation's environmental impact should be understood in a global context, acknowledging how some countries sustain their own environmental standards by degrading ecosystems elsewhere.

World System Theory is criticized as the assumptions that define its actual units are social systems that need to be examined. In addition, it neglects to study the economic success and the technological dynamism in the core countries. It also lacks generalization as the reaction to capitalist penetration was so different from place to place and continues to vary in important ways [44].

(2) The Treadmill of Production and Consumption Theory

The treadmill of production (TOP) is a theory introduced by Schnaiberg in 1980, arising from the impact of production processes on the environment and the variability of social and political responses to this impact in the last half of the 20th century. While some people opposed this modern production system, others believed new technologies as their best hope for solving environmental problems [45].

Schnaiberg and his collaborators outlined a new production system that affects the environment in two fundamental respects. First, as modern production systems were capital-intensive, more energy was needed to run machinery. In addition, the machinery was designed to increase production levels, thus requiring more raw materials causing excessive withdrawals from ecosystems and natural resource depletion. Second, modern production used new "efficient" energy/chemical intensive technologies to transform raw materials into finished products causing pollution [45].

The treadmill of production theorists is criticized as they consider production to be the prime mover of the treadmill, dismissing other dimensions, such as consumption, as decisions about the allocation of technologies are in the realm of production managers and owners. Thus, the initial interaction of social systems with ecosystems occurs within the production process [46,47]. Bell (2012) describes the logic of a "treadmill of consumption" that fills

in the economic gap of the treadmill of production theory [48]. The treadmill of consumption asserts that persons work hard to earn money to obtain desirable goods that will provide a sense of satisfaction; however, the standard of satisfaction always changes requiring more hard work and more consumption. This excessive consumption will cause resource depletion and pollution [35,48].

In this regard, while it seems obvious that efficiency improvement driven by advances in technology and organizational restructuring, must curb resource use, as it reduces the amount of resources used per unit of production or consumption, the Jevons paradox suggests that efficiency improvement has the potential to increase energy consumption and carbon dioxide emissions through its connection to growth of production and consumption [49].

In light of these theories, it makes sense to view the development of ICTs through a pessimistic lens. Developed countries use their ICT development to realize the efficient use of available resources causing resource depletion. Moreover, they exploit the resources of the less developed countries increasing the resource use profile of these countries with little of the benefit going to them [50,51].

(3) Structural Human Ecology

From a human ecology perspective, analyzing the environmental impact of human activity requires a multi-dimensional approach that considers population dynamics, economic development, and technological change. One foundational model in this context is the I=PAT identity, introduced by Ehrlich and Holdren (1971). This identity expresses environmental impact (I) as the product of three driving forces: Population (P), Affluence (A)—typically measured by GDP per capita—and Technology (T), which reflects the environmental impact per unit of economic activity [52].

The I=PAT model is valuable as an initial analytical tool because it highlights that no single factor acts in isolation—each component interacts multiplicatively with the others. However, the model has been subject to critique. Its two main limitations include:

1. Neglecting variable interactions—it assumes simple multiplicative relationships without allowing for more complex, interactive dynamics.
2. Ambiguity in variable specification—such as the assumption that individuals, rather than households or communities, are the most relevant units of analysis for environmental impact [53].

To address these shortcomings, Dietz and Rosa (1994) developed the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology), which reformulates I=PAT into a stochastic statistical model. This version allows for non-proportional and non-monotonic relationships among variables and incorporates error terms, making it more flexible and empirically testable [54]. The STIRPAT equation is:

$$I_i = aP_i^b A_i^c T_i^d e_i \quad (1)$$

The constant a scales the model; b , c and d are the exponents of P , A and T , respectively, that must be estimated and e is the error term. The subscript i indicates that the quantities (I , P , A , T and e) vary across observational units. The model can be expanded to incorporate additional factors such as urbanization, trade, and percent service economy [51].

Structural Human Ecology is an attempt to quantify the most important variables affecting environmental degradation. In addition, SHE leads to pessimistic views, but it is not fundamentally pessimistic, as data shows that increases in population and GDP strongly affect environmental degradation [35].

2.3. Empirical Literature Review

The interface between Information and Communication Technologies (ICTs) and environmental outcomes has become a pivotal topic in environmental economics. Moving beyond linear assumptions of technological determinism, emerging scholarship explores how ICT restructures economic systems, alters production functions, and modifies development trajectories that influence carbon emissions, with the relationship varying significantly—being positive, negative, or even negligible—depending on factors such as economic structure, energy sources, and policy environments. This evolving body of literature suggests that ICT's environmental impact is fundamentally an economic question of incentives, spillovers, and structural transformation.

2.3.1. ICT as a Transformative Input in Carbon-Intensive Production Functions

From a neoclassical and endogenous growth perspective, ICT is often modeled as a productivity-enhancing input. However, several studies demonstrate that ICT can act as a complementary factor to output expansion, leading to increased emissions in fossil-dependent economies. For instance, Khan et al. (2018) and Lee and Brahmasurene (2014) found that in emerging economies, ICT growth corresponds with higher CO₂ emissions, as it accelerates production without immediate substitution of clean energy [55,56].

Salahuddin and Ozturk (2016) show a similar pattern in OECD countries, suggesting that digitalization initially increases emissions through infrastructure demands, but may later enter a decoupling phase if supported by clean technologies. These findings resonate with the Environmental Kuznets Curve hypothesis, where environmental degradation first rises with income and ICT adoption, then falls after surpassing a threshold [57].

2.3.2. ICT-Driven Growth, Global Capital, and Emissions: The Role of FDI

Recent studies also explore how ICT interacts with foreign direct investment (FDI) and economic growth, shaping emission trajectories in developing countries. Nizam et al. (2020) examined Pakistan (1975–2017) using simultaneous equation modeling and ARDL testing. They found that while ICT and FDI contribute to GDP growth, they also raise carbon emissions in both short and long terms—highlighting a growth-emissions tradeoff in economies reliant on conventional energy [58].

In a broader cross-national context, Al-Mulali et al. (2015) demonstrated that FDI, in conjunction with ICT infrastructure, can either increase or reduce emissions depending on host countries' energy efficiency and technological capacity. Their analysis of 77 countries shows that while internet-based commerce reduces emissions, FDI inflows often amplify energy use unless directed toward cleaner sectors [59].

These studies support a dual-sector interpretation of the ICT-FDI-growth nexus: digital investment can lower transaction costs and enhance innovation, but if channeled into carbon-intensive production, it risks reinforcing environmentally harmful growth paths.

2.3.3. Digital Spillovers and Green Innovation in Emerging Economies

A more optimistic strand in the literature views ICT as a general-purpose technology (GPT) capable of stimulating green innovation. Haseeb et al. (2019) and Ozcan and Apergis (2018) found significant negative correlations between ICT penetration and CO₂ emissions across BRICS and emerging economies. Their results support theories of positive spillovers, where digital access fosters efficiency, enhances resource allocation, and supports lower-emission activities [60,61].

Lu (2018) and Zhang and Liu (2015) also demonstrate that ICT can indirectly reduce emissions by reorganizing industrial structure, improving energy intensity, and enabling decarbonization through digitized services. These findings align with endogenous growth theory, which posits that ICT not only increases productivity but also enhances the absorptive capacity of economies for sustainable technologies—particularly when coupled with domestic innovation systems [62,63].

2.3.4. Rethinking Externalities and Systemic Feedbacks: The ICT Rebound Challenge

While ICT promises efficiency, it also introduces systemic feedback loops that can undermine net environmental gains. Scholars like Plepys (2002) argue that digital efficiency may lead to rebound effects, where lower marginal costs encourage increased consumption and energy use—offsetting carbon savings [64]. Pamlin and Pahlman (2008) further stress the importance of accounting for ICT's direct, indirect, and systemic externalities, such as those associated with digital infrastructure, server energy use, and e-waste [64,65].

This aligns with critiques from ecological economics, which advocate for full-system accounting of ICT's role in economic activity. These perspectives highlight the need to move beyond traditional emissions accounting to frameworks that consider intersectoral energy redistribution and long-term ecological impacts.

The literature reveals that the relationship between ICT and carbon emissions can be positive, negative, or have no significant effect, depending on how ICT is embedded within economic systems. Its environmental impact is influenced by factors such as economic growth, foreign direct investment, and the degree to which ICT supports green innovation. Additionally, institutional quality and dependence on non-renewable energy play critical roles

in shaping outcomes. Thus, ICT's effect on emissions is not uniform but varies according to broader economic, structural, and institutional conditions.

2.4. Conceptual Framework

Figure 5 illustrates the conceptual framework that guides the current study. It depicts the pathways through which financial development, GDP growth, and natural resource rents influence carbon emissions. Digitalization is represented as a mediating factor that can either amplify or mitigate environmental impacts, depending on structural and policy contexts such as infrastructure quality, regulatory environment, and digital literacy.

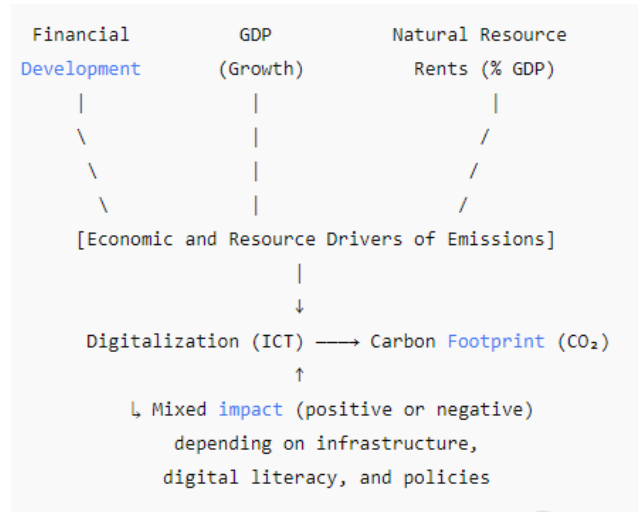


Figure 5. Conceptual Model of the Drivers of Carbon Emissions via Digitalization.

This framework is developed based on the preceding theoretical and empirical literature, which highlighted both optimistic and pessimistic perspectives on the role of ICT in shaping environmental outcomes, particularly within the MENA region.

3. Methodology

This section starts with sample description. Then model specification and variables are presented. Finally, the estimation method and results are discussed.

3.1. Sample Description

The empirical analysis includes panel data on years from 2000 to 2021 based on the availability of data. The sample includes 11 MENA countries excluding Bahrain, Djibouti, Jordan, Lebanon, Libya, Malta, Syria, Tunisia, West Bank and Gaza, and Yemen according to data availability. This makes a total of 242 country-year observations. However, the analysis is based on balanced dataset with missing data on some country-year observations. A common strategy for handling missing data is imputation, which involves maintaining all observations by replacing the missing values with likely estimates based on the available data. In the case of regression imputation, the substituted values are predicted from other variables, but this process does not contribute any new information. Alternatively, the most frequently used approach is to exclude any records containing missing data and analyze only the complete ones. This method, known as complete case analysis, available case analysis, or listwise deletion, is the default procedure in many statistical software programs [66].

3.2. Model Specification

To empirically investigate the effect of information and communication technology (ICT) along with selected macroeconomic and structural factors on environmental sustainability, this study employs a panel data econometric model. Specifically, the model examines how ICT development, real GDP, financial development, and natural

resource dependence influence carbon emissions—used here as a proxy for the carbon footprint due to their direct environmental relevance and widespread availability in international datasets.

The baseline model is specified as follows:

$$CO_{2it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 ICT_{it} + \alpha_3 RGDP_{it} + \alpha_4 FD_{it} + \xi_{it} \quad (2)$$

where $i = 1, 2, \dots, N$ and $t = 1, 2, \dots, T$ denotes the country and time period, CO_{2it} means the CO_2 emissions which are used as a proxy for the footprint variable due to data availability, GDP_{it} represents real GDP, $RGDP_{it}$ represents natural resources rents to GDP, FD_{it} stands for financial development (measured as monetary sector credit to private sector % GDP), ICT_{it} is a proxy for ICT and ξ_{it} is the error term.

The model captures both the direct environmental consequences of economic activity and the potential mitigating role of digital technologies. It is assumed that increased ICT penetration may contribute to lowering carbon emissions by improving energy efficiency, optimizing industrial processes, and supporting low-carbon innovation.

All data were obtained from the World Bank's World Development Indicators (WDI) database. Except for ratio-based variables (e.g., percentages), all variables were transformed into their natural logarithmic forms to reduce heteroskedasticity and allow for elasticity-based interpretation of coefficients.

The core variables in this study are the carbon footprint and information and communication technology (ICT), while other factors serve as control variables. Environmental sustainability is assessed through carbon dioxide (CO_2) emissions, measured in kilotons, in alignment with established empirical studies [57,59,60,63].

ICT development is conceptualized using the widely recognized three-stage model. The first stage, known as ICT readiness, reflects the level of infrastructure and access to ICT services. The second stage captures ICT usage and intensity, which represents how frequently and effectively ICT is used within society. The third stage—ICT impact—concerns the broader economic and societal outcomes resulting from digitalization. However, this study focuses on the first two stages: ICT readiness and ICT usage.

To operationalize ICT development, a digitalization index is constructed based on three indicators: the number of fixed telephone lines per 100 people and mobile cellular subscriptions per 100 people (both reflecting ICT readiness), and the number of internet users per 100 people (representing ICT usage and intensity) [57,58,60]. The average of these three indicators is used to create a composite proxy that reflects the overall level of ICT development across the sample countries.

In addition to ICT-related variables, the model incorporates several economic and structural controls. These include gross domestic product (GDP) [57–59,67], domestic credit to the private sector as a percentage of GDP, which serves as a proxy for financial development [57,60], and the share of natural resource rents in GDP. These variables have been widely documented in prior literature as influential in shaping the relationship between ICT and carbon emissions, particularly in the context of economic growth, financial capacity, and resource dependence [8].

Empirically, we anticipate a positive regression coefficient for α_1 , as this aligns with the potential presence of the Environmental Kuznets Curve (EKC) hypothesis. Similarly, a positive value for α_3 is expected, since higher natural resource rents—such as those from oil, gas, coal, minerals, and forests—are likely to lead to increased carbon emissions. Financial development significantly contributes to economic growth, and one pathway through which it may elevate CO_2 emissions is by supporting industrial and manufacturing activities. The financial sector facilitates this by offering credit and loans, reducing financing costs, mitigating operational risks, and ultimately stimulating production, which results in higher emissions. Lastly, the effect of Information and Communication Technology (ICT) on environmental outcomes has been inconclusive, with the literature presenting mixed findings [56].

3.3. Estimation Method

The asymptotic properties of dynamic panels with both large cross-sectional units (N) and long time dimensions (T) differ from those of traditional panels characterized by large N and small T . In small T panels, estimation typically relies on fixed or random effects models. However, as time observations increase—as is the case with large N and large T panels—it becomes crucial to conduct stationarity and cointegration tests to determine the appropriate model specification [68].

This study examines the impact of digitalization on the carbon footprint across 11 MENA countries over the period 2000–2021. For the short-run analysis, the Generalized Method of Moments (GMM) estimator developed

by Arellano and Bond (1991) is employed. GMM is a consistent estimator that utilizes lagged dependent variables and predetermined instruments, effectively addressing endogeneity issues common in panel data. Moreover, GMM accommodates heterogeneity and diverse distributional assumptions, making it suitable for a variety of model specifications [67,68].

For long-run analysis, unit root tests—such as the Im, Pesaran, and Shin (IPS) test and Pesaran's Cross-sectionally Augmented Dickey-Fuller (CADF) test—are used to determine the integration order of each variable [68]. If the variables are found to be stationary, panel data models such as pooled OLS, fixed effects, or random effects are applied.

In contrast, if the variables are non-stationary, cointegration tests such as the Kao test and the Pedroni tests (Kao, 1999; Pedroni, 1999, 2004) are employed to verify the existence of a long-run equilibrium relationship among the variables. Upon establishing cointegration, the Fully Modified Ordinary Least Squares (FMOLS) method is applied to estimate the long-run relationship. FMOLS addresses key issues like serial correlation and endogeneity, which are often problematic in standard OLS estimations, and helps reduce bias in small sample contexts [69].

Finally, the Dumitrescu Hurlin Panel Causality Test is employed to check causal relationship between the information and communication technology and the carbon footprint in the MENA region.

4. Empirical Results and Discussion

4.1. Pre-Elementary Procedures of Panel Data

First, understanding the relationship between information and communication technology (ICT) development and carbon dioxide emissions ($\ln CO_2$) in the MENA region is essential for assessing whether the digital transformation in these countries contributes to environmental pressures or, conversely, supports more sustainable development. To provide a preliminary visual insight into the nature of this relationship, a scatter plot was constructed, plotting $\ln CO_2$ against ICT across multiple countries and time periods.

Figure 6 reveals several notable patterns. Most prominently, the data points form distinct horizontal clusters, which likely reflect country-specific fixed effects—that is, systematic differences in CO_2 emission levels across countries, regardless of ICT variation. Within these clusters, some degree of variation in ICT can be observed, yet no consistent linear pattern emerges. This suggests that the relationship between ICT and CO_2 emissions is not uniform across countries and may depend on a range of structural or contextual factors, such as energy sources, digital infrastructure efficiency, or national environmental policies. Furthermore, the plot shows that the variance in CO_2 emissions tends to narrow at higher levels of ICT, which may indicate a convergence effect among digitally advanced countries.

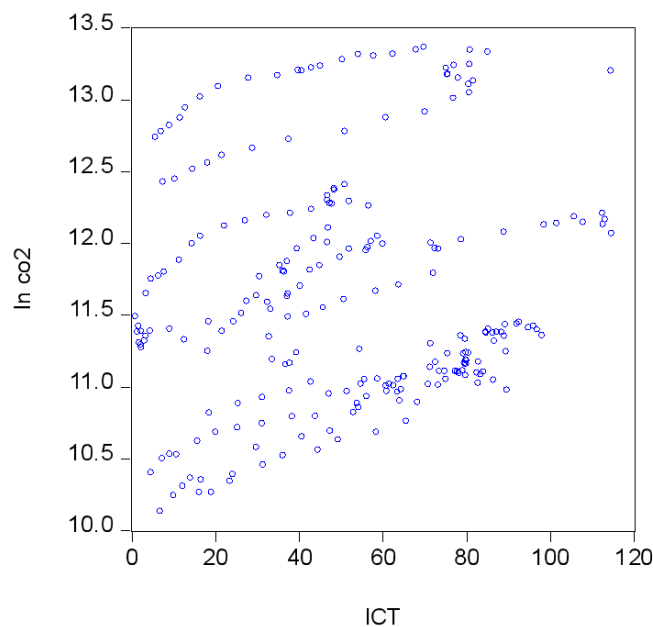


Figure 6. Scatter Plot of $\ln CO_2$ Against ICT.

Second, the study conducted the pre-elementary procedures of panel data; the panel cross section dependence tests, namely, Breusch-Pagan LM, Pesaran scaled LM, Bias-corrected scaled LM and Pesaran CD and the homogeneity test according to the Hsiao strategy.

Table 2 reports the results of CD tests, which indicate the rejection of the null hypothesis of no cross-section dependence at a 1 % significance level. This outcome implies that the panel data suffer from CD problem across cross-sections and the chosen parameters during the period of study.

Table 2. Panel Cross-Section Dependence Estimations.

Variable	Breusch-Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM	Pesaran CD
CO ₂	884.8085*** (0.0000)	79.11913*** (0.0000)	78.84413*** (0.0000)	28.82693*** (0.0000)
ICT	1093.318*** (0.0000)	98.99977*** (0.0000)	98.73787*** (0.0000)	33.04505*** (0.0000)
LnGDP	1068.378*** (0.0000)	96.62184*** (0.0000)	96.35993*** (0.0000)	32.62952*** (0.0000)
FD	575.7478*** (0.0000)	49.65136*** (0.0000)	49.38945*** (0.0000)	7.559613*** (0.0000)
RGDP	522.6374*** (0.0000)	44.58748*** (0.0000)	44.32557*** (0.0000)	17.97351*** (0.0000)

Note: *** P < 0.01.

Table 3 represents the results of the homogeneity test for the model. The null hypothesis (the slope coefficients are homogenous) was rejected since the probability values of the test findings were less than 1% and 5%, and the heterogeneity of the cointegration coefficients was established. Therefore, to establish an unbiased and consistent estimation, we should first apply the Pesaran CADF second-generation panel unit root test.

Table 3. Homogeneity Test Result.

Hypotheses	F-Stat	P-Value
H1	482.4330	$5.3 \times 10^{-156}***$
H2	12.28118	$2.73 \times 10^{-32}***$
H3	738.1720	$8.1 \times 10^{-155}***$

Note: *** P < 0.01.

Since there is across-section dependence for all variables, as mentioned previously, it is better to employ the Pesaran CADF second generation unit root test to assess the order of integration for the concerned variables. The panel unit root test indicates that all the variables are non-stationary at level as reported in **Table 4**.

Table 4. Pesaran Second-Generation CADF Panel Unit Root Test Results.

Variable	Level		Difference		Decision
	Deterministic Term	p-Value	Deterministic Term	p-Value	
LnCO ₂	Trend and intercept	-5.613 (0.000)	Trend and intercept	-0.287 (0.387)	I(1)***
ICT	Trend and intercept	0.417 (0.662)	Trend and intercept	-4.676 (0.000)	I(1)***
LnGDP	Trend and intercept	1.088 (0.862)	Trend and intercept	-6.125 (0.000)	I(1)***
FD	Trend and intercept	1.762 (0.961)	Trend and intercept	-7.328 (0.000)	I(1)***
RGDP	Trend and intercept	2.534 (0.994)	Trend and intercept	-4.942 (0.000)	I(1)***

Note: Standard errors are in parentheses. *** P < 0.01.

Second, to examine whether a long-term relationship exists between digitalization and the carbon footprint the study applies the seven cointegration tests developed by Pedroni (1999, 2004) alongside Kao's (1999) test, both of which test the null hypothesis of no cointegration. Kao's test assesses cointegration under the assumption of cross-sectional homogeneity, whereas Pedroni's method accounts for heterogeneity under the alternative hypothesis [70]. The heterogeneous panel cointegration approach introduced by Pedroni (1999, 2004), which accommodates cross-sectional dependence and individual-specific effects, is applied as follows:

$$CO_{2it} = \gamma_{it} + S_i t + \gamma_{1i} ICT_{it} + \gamma_{2i} GDP_{it} + \gamma_{3i} FD_{it} + \gamma_{4i} RGDP_{it} + \xi_{it} \quad (3)$$

where $i = 1, \dots, N$ for each country in the panel and $t = 1, \dots, T$ refers to the time period. CO_{2it} represents the carbon-dioxide emissions. The parameters γ_{it} and S_i allow for the possibility of country-specific fixed effects and deterministic trends, respectively. ξ_{it} denotes the estimated residuals, which represent deviations from the long-run relationship.

To test the null hypothesis of no cointegration, $\rho_i = 1$, the unit root test is conducted on the residuals as follows:

$$\epsilon_{it} = \rho_i \epsilon_{it-1} + w_{it} \quad (4)$$

Pedroni (1999, 2004) introduces two categories of cointegration tests. The first category includes panel tests based on the within-dimension approach (panel cointegration statistics), which consist of four statistics: panel v -statistic, panel ρ -statistic, panel PP-statistic, and panel ADF-statistic. These tests combine the autoregressive coefficients across countries when conducting unit root tests on the residuals, while accounting for both common time effects and cross-country heterogeneity. The second category consists of group tests based on the between-dimension approach (group mean panel cointegration statistics), which include the group ρ -statistic, group PP-statistic, and group ADF-statistic. These tests rely on the average of the individual autoregressive coefficients derived from unit root tests on each country's residuals. All seven statistics follow an asymptotic standard normal distribution. The panel v -statistic is a one-sided test where higher positive values lead to rejection of the null hypothesis of no cointegration, while for the other six statistics, larger negative values indicate rejection of the null hypothesis [71]. **Table 5** presents both within- and between-dimension cointegration test results, showing that the panel ADF-statistic, group PP-statistic, and group ADF-statistic reject the null hypothesis of no cointegration at the 1% significance level.

Table 5. Pedroni Cointegration Test Result.

Within Dimension		Between Dimension	
Test Statistics		Test Statistics	
Panel v -statistic	-0.299914 (0.6179)	Group ρ -statistic	3.859511 (0.9999)
Panel ρ -statistic	2.732788 (0.9969)	Group PP-statistic	-3.980320 (0.0000)***
Panel PP-statistic	0.081838 (0.5326)	Group ADF-statistic	-4.209579 (0.0000)***
Panel ADF-statistic	-3.174481 (0.0008)***		

Note: Standard errors are in parentheses. *** $P < 0.01$.

Kao's (1999) test is also employed to investigate the long-run relationship between the variables. **Table 6** reports the result of the test. The test reveals that there is a cointegration relationship between the dependent variable and the independent variables. Hence, the cointegration exists for the estimated model.

Table 6. Kao Cointegration Test Results.

Dependent Variable	t-Statistics
$\ln CO_2$	-2.793381 (0.0026)***

Note: Standard errors are in parentheses. *** $P < 0.01$.

4.2. Short Run Estimation

After completing the preliminary steps for panel data estimation, we proceed to estimate the short-run relationships using the system Generalized Method of Moments (GMM). The results of this estimation are presented in **Table 7**. Furthermore, the post-estimation diagnostics in Table 7—specifically the Sargan test for over-identification and the test for instrument validity—do not reject the null hypothesis. This suggests that the GMM estimation does not face issues related to over-identification.

Table 7. GMM Estimation for the Model.

Dependent Variable	LnCO ₂
Constant	0.3336255* (0.057)
ICT	-0.000067 (0.755)
LnGDP	-0.0019699 (0.717)
FD	-0.0004962* (0.067)
RGDP	0.0016049*** (0.000)
Sagran	193.0273 (0.0602)

Note: The one-step GMM estimator is used as the variance-covariance matrix in the GMM two-step estimator is not full rank. In addition, the lagged difference of the dependent variable is used as the instrument in the model. Standard errors are in parentheses. *** P < 0.01, *P < 0.1.

The Generalized Method of Moments (GMM) estimation results reveal that, in the short run, information and communication technology (ICT) does not exert a statistically significant impact on carbon emissions. This outcome may stem from the transitional nature of ICT adoption across MENA countries, where digital infrastructure remains under development, and emissions-reducing applications—such as smart grid integration or IoT-based environmental monitoring—are not yet fully deployed. While several countries in the region are pursuing digital decarbonization strategies, such as improving energy efficiency and automating carbon-intensive sectors, the lag between ICT investment and environmental outcomes may explain the lack of short-term statistical significance [21].

Similarly, economic activity (GDP) does not show a significant effect on carbon footprint in the short term, which could be attributed to the ongoing diversification of energy portfolios in MENA economies. Many countries are adopting a dual-energy model, combining fossil fuels with increasing renewable energy shares, while maintaining relatively stable emissions levels. This balance, supported by moderate technological capacity and energy subsidies, may buffer short-run fluctuations in carbon output despite variations in economic growth [67].

Conversely, the model reveals that financial development has a statistically significant and negative short-run impact on CO₂ emissions. Specifically, a 1% increase in financial development corresponds to a 0.0004% reduction in emissions. This finding suggests that short-term capital flows—particularly credit extended to green initiatives or clean technology adoption—can deliver immediate environmental benefits, especially when supported by favorable regulatory environments and access to environmentally responsible investment channels [25]. It also reflects the growing role of financial institutions in climate-sensitive investment decisions and sustainability-linked lending frameworks.

In contrast, the results indicate that natural resource abundance contributes to increased emissions in the short run. A 1% rise in natural resource rents is associated with a 0.0016% increase in CO₂ emissions. This effect is particularly evident in resource-rich oil-exporting countries such as Saudi Arabia, where energy production remains largely dependent on hydrocarbons. Despite recent efforts to shift toward renewable energy sources, the structural inertia of fossil-fuel-driven economies limits short-term decarbonization gains, making emissions more sensitive to fluctuations in resource extraction and export volumes [21].

These short-run findings underscore the importance of policy timing and structural reform. While ICT and financial systems hold potential for environmental improvement, their impact is often delayed and depends on supportive institutional mechanisms, market incentives, and technological diffusion.

4.3. Long Run Estimation

The long-run dynamic relationships are estimated by the fully modified ordinary least squares (FMOLS) technique. **Table 8** shows the long-run estimation results.

Table 8. FMOLS Estimation for the Model.

Dependent Variable	LnCO ₂
ICT	0.006118*** (0.000742)
LnGDP	0.341125* (0.062117)
FD	0.000890*** (0.000723)
RGDP	-0.004878*** (0.001455)

Note: Standard errors are in parentheses. *** P < 0.01, *P < 0.1.

The results of the long-run panel analysis using Fully Modified Ordinary Least Squares (FMOLS) estimation

reveal nuanced relationships between ICT development, economic growth, financial expansion, natural resource rents, and carbon dioxide emissions—each with distinct implications for environmental sustainability.

Contrary to expectations, the analysis indicates that a 1% increase in ICT development is associated with a modest 0.0061% increase in CO₂ emissions over the long term. While ICT is widely promoted as a tool for enhancing energy efficiency, optimizing industrial systems, and supporting data-driven environmental policies, this counter-intuitive result may reflect a rebound effect, where increased digital infrastructure leads to higher energy demand (e.g., from data centers, network infrastructure, and digital device usage). Furthermore, the benefits of ICT—such as demand-side management and smart environmental monitoring—may be undermined by rapid economic expansion and population growth, particularly in regions lacking strong environmental governance or digital literacy frameworks [21,72,73].

In terms of economic activity, the model shows that a 1% increase in GDP results in a 0.34% rise in CO₂ emissions. This strong positive relationship supports the Environmental Kuznets Curve (EKC) hypothesis in its early stages, where economic growth in resource-dependent or industrializing economies initially leads to environmental degradation. The rise in emissions can be attributed to increased consumption, production, and energy use, particularly in energy-intensive sectors such as manufacturing, construction, and water desalination, which is prevalent in arid regions [67].

Similarly, financial development is found to significantly increase carbon emissions in the long term, with a 1% improvement in credit availability correlating with a 0.00089% increase in emissions. While financial deepening theoretically supports green innovation, in practice, it may enable higher levels of consumption and investment in carbon-intensive sectors, especially in economies where green lending standards, digital inclusion, and environmental awareness remain underdeveloped. This underscores the need for redirecting financial flows toward sustainable ICT and cleantech solutions [21].

On a more positive note, the findings suggest that natural resource rents can help reduce emissions over time. Specifically, a 1% increase in the share of natural resource rents in GDP is associated with a 0.0048% decline in CO₂ emissions. This inverse relationship may be explained by proactive conservation policies and environmental investments undertaken by resource-rich countries—particularly oil-exporting nations—in response to international climate obligations, ESG investment pressures, and the desire to diversify away from hydrocarbons [21].

Together, these results highlight that ICT alone cannot guarantee environmental improvement unless it is strategically integrated into broader sustainability frameworks—including smart urban planning, environmental regulation, financial incentives, and public engagement mechanisms. This reinforces the importance of context-sensitive ICT deployment, particularly in emerging economies navigating the trade-offs between growth and environmental responsibility.

4.4. The Dumitrsc-Hurlin Causality Test Results

Subsequently, a causality test is conducted to investigate the direction of causality between the variables. Hurlin's (2008) test is based on the null hypothesis of no-Granger causality. Under the alternative hypothesis, there exist two subgroups of units: one with causal relationships from x to y , but not necessarily with the same data-generating process; and another subgroup where there are no causal relationships from x to y [70]. **Table 9** summarizes the Dumitrescu Hurlin Panel Causality Test output for the information and communication technology and the carbon footprint in the MENA region.

Table 9. Pairwise Dumitrescu Hurlin Panel Causality Tests.

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
LnCO ₂ does not homogeneously cause ICT	1.65636	0.97557	0.3293
ICT does not homogeneously cause LnCO ₂	5.37891	7.91904	2.E-15

The results of the Pairwise Dumitrescu-Hurlin Panel Causality Test for the MENA region, covering the period 2000–2021 with one lag, provide important insights into the dynamic relationship between ICT development and carbon footprint, as proxied by CO₂ emissions. The null hypothesis that CO₂ emissions (LN_CO₂) do not homogeneously Granger-cause ICT cannot be rejected at conventional significance levels (W-stat = 1.65636; $\bar{Z}$ -stat =

0.97557; p-value = 0.3293). This suggests a lack of statistically significant evidence to support the existence of a causal linkage from environmental degradation to ICT development across the panel.

Conversely, the test strongly rejects the null hypothesis that ICT does not homogeneously Granger-cause CO₂ emissions (W-stat = 5.37891; Z-stat = 7.91904; p-value < 0.01). This indicates robust evidence of unidirectional causality running from ICT to CO₂ emissions in the MENA region. Such a result implies that advancements in ICT infrastructure, usage, and diffusion may contribute to changes in environmental outcomes—likely through increased electricity consumption, data transmission, and expansion of digital services, all of which can elevate energy demand and emissions if not supported by green technologies.

These findings align with the notion that while ICT is often posited as a tool for improving environmental efficiency, its expansion—particularly in regions still reliant on fossil fuels—may initially exacerbate environmental pressures. The absence of reverse causality further suggests that environmental degradation does not serve as a significant determinant of ICT investment or adoption in the region. These results have policy implications, highlighting the need for integrating sustainable energy strategies within the digital transformation agendas of MENA countries.

5. Conclusions

This study set out to examine the environmental effect of Information and Communication Technologies (ICT) in the MENA region, particularly focusing on whether digitalization contributes to a reduction in carbon footprint. Contrary to the common narrative that ICT enhances energy efficiency and promotes decarbonization, our empirical findings indicate a long-run positive effect of ICT expansion on carbon emissions. This suggests that ICT, in its current implementation across the region, is contributing to environmental degradation—likely reflecting the energy efficiency–consumption paradox, where efficiency gains are offset by increased usage and energy demands from digital infrastructure, such as data centers and smart devices.

These findings align with recent literature that emphasizes the conditional and context-dependent nature of ICT's environmental impact. While theoretical models and case-specific studies demonstrate that AI-driven monitoring systems, smart environmental governance platforms, and digital tools for waste and energy management can reduce emissions through enhanced efficiency and responsiveness [74,75], these benefits are not automatically realized at a macroeconomic scale. Instead, the carbon footprint of ICT depends on factors such as energy mix, regulatory environment, and how digital technologies are integrated into production and consumption systems.

Policy Recommendations

To reconcile the potential of ICT with sustainable development goals, the following policy directions are recommended:

(1) Green and Smart Digital Infrastructure

Governments should accelerate the transition toward sustainable ICT systems by investing in low-emission data centers, energy-efficient telecommunications networks, and green cloud computing. Integrating IoT-enabled energy monitoring within urban infrastructure is essential for building smart cities that optimize electricity, water, and transport usage in real time.

(2) Environmentally-Oriented Digital Regulation

Policy frameworks must require digital firms and ICT-intensive industries to disclose carbon data, meet eco-efficiency benchmarks, and implement life-cycle environmental audits. In IoT ecosystems, regulation should focus on managing energy demand and e-waste while ensuring interoperability and data sustainability.

(3) Green Financial Channeling

Given the observed positive link between financial development and carbon emissions, financial flows should be redirected toward green fintech, climate-conscious venture capital, and clean-tech enterprises. This could support digital innovations such as IoT-based pollution sensors, smart grids, and AI-driven sustainability platforms.

(4) Targeted ICT Deployment in High-Impact Sectors

ICT and IoT should be promoted in sectors with high decarbonization potential—such as intelligent transport systems, renewable energy grids, smart agriculture, and waste management. Meanwhile, governments must monitor and regulate carbon-intensive ICT applications like data mining or inefficient logistics systems in e-commerce.

(5) Regional Smart City Alliances and Data Sharing

Sharing Encourage regional cooperation—especially across the MENA region—on smart city development, green digital infrastructure, and shared sustainability metrics. Joint platforms for real-time data exchange and coordinated ICT standards can drive collective environmental innovation.

(6) Citizen-Centric Environmental Digitalization

Environmental governance should not be top-down only; citizens must be empowered to participate. Mobile apps, open data portals, and community-based IoT devices can help involve residents in monitoring urban pollution, reporting environmental hazards, and shaping sustainable behavior at the local level.

In sum, ICT alone is not a silver bullet for carbon reduction. Its environmental benefits depend on policy frameworks that shape how digital technologies are developed, deployed, and powered. With the right governance and investment strategies, digitalization can serve as an enabler—not an obstacle—to a low-carbon future.

Future research should address the limitations of national-level analysis by incorporating sectoral-level disaggregation, especially in areas like transport, manufacturing, and energy, where ICT's environmental impact may vary significantly. Due to data unavailability during our study period, we could not explore these differences, but future studies should aim to use more granular data to assess sector-specific effects. Additionally, research should investigate non-linear relationships, threshold effects, and include ICT lifecycle emissions—from production to disposal—to capture the full environmental footprint. Advanced econometric techniques and policy impact evaluations could also provide deeper insights into how digitalization can be aligned with sustainable development goals.

Author Contributions

Conceptualization, M.M. and D.M.I.; methodology, M.M.; software, M.M.; validation, M.M., O.H., and D.M.I.; formal analysis, M.M.; investigation, M.M.; resources, M.M.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, M.M., O.H., and D.M.I.; visualization, M.M.; supervision, O.H. and D.M.I.; project administration, M.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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