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Research Article

E-government, innovation, and renewable energy transition: A triadic model for pollution reduction in developing economies

Md Qamruzzaman[a,*], Salah Abosedra[b], Syed Nazmus Sakib[c]

[a]*School of Business and Economics, United International University, Dhaka, Bangladesh*
[b]*School of Human and Social Sciences, Libyan International University, Benghazi, Libya*
[c]*School of Engineering, Faculty of Science and Engineering, Macquarie University Sydney, Australia*

Abstract. In developing economies, the pressure to achieve environmental sustainability is growing as digital transformation and energy transition take precedence. However, empirical evidence on the relationship between digital governance, the adoption of technological innovations, and renewable energy, and its impact on the environment is still scarce. This study investigates the direct and interactive effects of e-government, technological innovations, and renewable energy use on pollution reduction in the Next Eleven (N-11) economies from 2003 to 2022. This study proposes a triadic framework for the direct and indirect effects of digital governance on the environment based on two theoretical models: the Environmental Kuznets Curve (EKC) and the Technology Acceptance Model (TAM). Per capita CO_2 emissions were used as a proxy for environmental quality, and the United Nations E-Government Development Index (EGDI) was used as a proxy for e-government. Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL), Common Correlated Effects Mean Group (CCEMG), Augmented Mean Group (AMG), and dynamic generalised method of moments (GMM) estimators are employed to solve the problems of cross-sectional dependence, heterogeneity, endogeneity, and dynamic relationships. The results show that e-government has a significant negative effect on environmental pollution in both the short and the long run. Technological advancements and the use of renewable energy have their own impacts on reducing emissions and enhancing the environmental impact of digital governance. The results of the marginal effects analysis also show that the pollution-decreasing effect of digital governance increases significantly with improvements in innovation and renewable energy use. Human capital development and environmental taxation contribute to improving the environment, whereas dependency on natural resources creates environmental pressure. The findings of this study assist in growing the literature on digital sustainability by offering evidence that three case variables–digital governance, technological innovation, and renewable energy transition – are complementary drivers of environmental performance in developing economies. The results indicate that policies to foster integrated digital governance systems, innovation ecosystems, and renewable energy growth could help accelerate pollution reduction and transition to more sustainable models of development in emerging economies.

Keywords: Government digitization; Pollution reduction; Technological innovation; Renewable energy; N-11 countries

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1. Introduction

The organisation of pollution minimisation needs to be multidimensional, combining stringent environmental regulations, emerging technologies, and green government strategies. This will help address both economic and ecological issues. Recent studies suggest that the manner in which energy is consumed in rapidly developing economies is a key factor in the unusual ways in which pollution occurs. This explains the necessity of aligning policies with the development direction of each country and the structure of its industry (Sinha *et al*, 2017). According to Wang *et al* (2022) stated that one strategy is to adopt renewable energy. An increase in renewable energy consumption reduces the ecological footprint when effective democratic institutions and extensive regulations are in place. FDI can also increase pollution. However, it can become an engine for sustainable development and greener air once it goes green (Padhan & Bhat, 2023). It has become increasingly evident that the law alone is insufficient and must be complemented by the enhancement of energy efficiency and models founded on the principles of a circular economy. It is becoming increasingly evident that the law alone is insufficient and must be complemented by the enhancement of energy efficiency and models founded on the principles of a circular economy. Collective strategies have higher and longer-term environmental payoffs. In short, policymaking and policy implementation should be coordinated, renewable energy should be encouraged, and environmentally friendly FDI should be developed with the help of eco-innovation to minimise pollution and guarantee sustainable development of the region in the long run (Cruz-Pérez *et al.*, 2024).

Over the past two decades, climate change has necessitated the exploration of the relationship between digital change, technology development, and sustainability. Among these topics is the contribution of government digitisation to policy revolution, especially in terms of pollution regulation. Digital presence in the public sector enhances efficiency and

* Corresponding author:
Email: qamruzzaman@bus.uiu.ac.bd (Md Qamruzzaman)

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directly and quantifiably impacts the environment by informing decisions based on data, promoting smart infrastructure, and making resource allocation more rational (Janowski, Estévez, & Baguma, 2018). Digital initiatives that can benefit the environmental management process include e-governance, open data portals, and automated monitoring, as they make the process more transparent and responsive. Digitalisation enables the control of emissions, monitoring of compliance, and the establishment of innovation systems in line with environmental objectives (Song, Li, & Feng, 2024). However, the impact of digitalisation on pollution is not always proportional and can depend on other aspects, including the extent of technological development and the share of renewable energy in a country's energy mix.

Technological innovation, particularly in clean technology, plays a crucial role in minimising environmental degradation. In the investigation of G-20 countries (Han, Peng, Guo, Aslam, & Xu, 2025), technical progress not only promotes renewable energy but also reduces the CO 2 concentration particularly when the government supports it with policies and expenditure on R&D. The same study demonstrated that renewable energy can decrease pollution, substitute fossil fuels, decrease greenhouse gases, and enhance air quality (Adanma & Ogunbiyi, 2024). The article presented case studies, such as the transition to renewables in Copenhagen, which demonstrated that the use of digital innovation and effective legislation can significantly reduce urban emissions through the adoption of renewable energy, serving as an example for other cities (Christensen, 2024). The proposed triadic framework can be embedded in the general debate on digital public administration and environmental policy, as supported by recent studies on AI-enabled digital transformation. AI readiness is a key factor in enhancing business process efficiency, as demonstrated by (Devianto *et al.,* 2025; Salam, Radović-Marković, Farooq, Marković, & Vučeković, 2026), who highlighted the potential of AI in driving digital transformation and thereby improving performance. This logic is applicable to e-government, as digitally prepared public agencies can process information related to the environment more quickly, monitor compliance, and contribute to cleaner administration. Likewise, (Salam *et al.,* 2025)pointed out the importance of privacy issues, responsible implementation, and ethical leadership in the acceptance of AI-based systems in the RAIDUA model. These findings reinforce the theoretical correlation between TAM and environmental governance by demonstrating the need to build trust, usefulness, and institutional design in technology adoption. Hence, it is crucial to consider the triple mechanisms of digital governance, green technological innovation, and renewable energy use to reduce pollution levels in emerging economies.

In previous studies, we understood the effects of individual variables, including government digitisation, technological innovation, and renewables, on sustainability; however, some gaps remain in the literature. Most studies separate these factors rather than examine their interaction and multiplier effects. Indicatively, (P. Wang, Han, Rizvi, & Naqvi, 2022) demonstrated that the digital tools of the government can reduce the use of fossil fuels and maximize efficiency through the use of electricity by the government through improved administration. However, they did not consider the possibility of variance in these gains in the presence of other facilitating variables, such as technological innovation or green infrastructure. However, these factors have not been thoroughly tested as moderators. Although technological innovation can enhance the adoption of renewables and improve pollution performance (Han *et al.*, 2025), most studies have focused on developed economies or certain industries. There is a lack of documentation on the complex interactions between innovation and energy transitions in digital governance, particularly in emerging or transitional economies. Recent meta-reviews on the adoption of renewables have focused on policy frameworks and innovation ecosystems in the realisation of environmental objectives (Adanma & Ogunbiyi, 2024), but seldom include the role of digital governance as the institutional support that enables the system to coordinate them all. The possibility that government digitisation can become a catalyst for spreading technology, simplifying renewable implementation, and enhancing environmental observation processes remains to be explored.

2. Literature review and hypothesis development

This section describes the conceptualisation of government digitisation and pollution reduction and explains the theoretical relationships that support planned relations and mitigate their impacts. Its synthesis is based on literature that operationalises e-government as a service provision, as well as a transformation to infrastructure, and packages environmental outcomes using a well-known sustainability theory. It asserts that technological innovation and the adoption of renewable energy soft power solutions operationalise digitisation in relation to environmental performance.

The literature views government digitisation as a multidimensional process that integrates the delivery of digital services (e-governance/e-government platforms), the presence of digital infrastructure (ICT and data environments), and the utilisation of data analytics in government tasks (Alfiani *et al.,* 2024). E-government maturity and information quality focus on the delivery of services to citizens at a functional level, not as an act of creation, but as a result of the technological and organizational capabilities necessary to maintain those services. This means that digitisation should be operated as a combination of platform quality, data governance, and institutional capacity, instead of being a single technological artefact (Musah *et al.,* 2022; Patergiannaki & Pollalis, 2022). Empirical research indicating the relationship between e-government development and environmental performance states that with better information dissemination and transparency through e-government, it is more straightforward to oversee centrally and enforce local environmental regulations, better control regulatory compliance, and improve environmental performance (Mu, Liang, & Yang, 2025; Xie *et al.,* 2023). Similar studies note that user trust, the quality of the provided platforms, and the presence of people are crucial mediating variables through which digitisation influences governance outcomes, and a socio-technological approach to the issue can be reviewed as one in which consumer participation, institutional design, and digital systems co-determine the consequences (Wa & Zhang, 2023; Zhong, 2022).

Three theoretical frameworks explain why digitisation can impact environmental governance. First, New Public Management (NPM) models assume that digitalisation promotes the principles of efficiency, transparency, and the provision of services to clients. Consequently, e-government can lower transaction costs, accelerate regulatory procedures, and make enforcement more transparent, thereby driving the environmental governance agenda (Chen & Li, 2024; Kyeong, Ra, Park, & Im, 2022). Second, information asymmetry theory implies that digital platforms and data analytics can minimise the informational asymmetry between customers, selections, and citizens, enhancing the monitoring of progress, reducing the expenses of enforcement, and augmenting compliance, as evidenced by studies highlighting the importance of e-government in terms of accelerating information flows and more centralised oversight (Mensah & Mwakapesa, 2023; Mu *et al.*, 2025). Third, institutional theory highlights that course to regulatory structures, administrative capabilities, and institutional incentives, the type of digital intervention should lead to environmental impact: weak institutions or perverse local incentives (including fiscal ties that promote laxity in regulations) tend to dull a digital intervention, but alignment of policy tools and institutional incentives will increase efficacy (Ramadani, Yovadiani, & Dewi, 2022; Rongjuan, 2022; Zhu, Meng, & Teng, 2024).

The reviewed literature defines pollution mitigation using standard environmental metrics, such as CO_2 emissions and particulate matter (for example, PM2.5), as well as composite ecological and carbon footprint measures. The impact of the digital economy on the environment is often measured in terms of CO_2 emissions or city carbon footprints to estimate the net environmental impact of digitisation (Dong & Yao, 2024; H. Liu, Wang, & Shen, 2023). Theoretical mapping situates pollution reduction within a broader sustainability context. According to the ecological modernisation theory, technological change and economic modernisation, which are usually facilitated by digitisation, can decouple economic growth and environmental degradation and make production cleaner, more efficient, and increasingly green ((G. George, Merrill, & Schillebeeckx, 2020; Xie *et al.,* 2023) Closely related, the Environmental Kuznets Curve (EKC) hypothesis supports several empirical studies on digitalisation and emissions, which implicitly argues that at some level of development or digitisation, the quality of the environment will be enhanced. However, empirical conclusions are heterogeneous and depend on geographical location and energy structures, and some studies have shown an immediate rising energy demand and emission level in regions below the EKC turnaround point (Shen *et al.,* 2022; Zhong, 2022).

According to the Diffusion of Innovations Theory and Schumpeterian creative destruction, innovation facilitates the creation and introduction of cleaner production technologies and digitisation-based tools to improve monitoring and efficiency in business processes, thereby increasing the potential of digitisation to reduce pollution. The empirical research is based on H. Liu et al. (2023); Xie *et al.* (2023) discovers avenues through which digital technologies can decrease emissions through their better energy efficiency, growth of green technologies, and virtual economic action (virtual agglomeration). The use of renewable energy is operationalised in terms of the proportion of renewable energy within the energy mix or installed renewable capacity. The effects of interaction take the form of the idea that digitisation can maximise the introduction of renewables (such as smart grids and demand response), and the process of integrating renewables reduces the carbon intensity of digital activity, leading to a synergistic decrease in pollution (Adha, Hong, Agrawal, & Li, 2022; Dong & Yao, 2024). The effects of interaction take the form of the idea that digitisation can maximise the introduction of renewables (such as smart grids and demand response), and the process of integrating renewables reduces the carbon intensity of digital activity, leading to a synergistic decrease in pollution. The most prosperous notions view technological invention and renewable energy adoption as co-varied intermediaries. Technological innovation generates digital and energy technologies that make digitisation cleaner and reduce its carbon footprint. These mechanisms are conditional on institutional quality and civic engagement, which determine the incentives for adoption and compliance (Wa & Zhang, 2023). Thus, a holistic model hypothesizes that government digitization abates pollution to the levels that it is institutionalized in the innovation-enabling institutions and is accompanied by a shift towards renewables; without any of these moderators, the net environmental impact of digitization might be zero or even negative as a result of energy consumption or government failures (Ramadani *et al.,* 2022; Shen *et al.,* 2022)

2.1. E-Government effects on pollution reduction

Digital governance, also known as e-governance, refers to the use of Information and Communication Technologies (ICTs) by governments to enhance their services to the public, improve administrative efficiency, and increase transparency. It will involve online services, digital archives, mobile applications, and electronic communication services, enabling government agencies, individuals, and business organisations to communicate more readily. The first indicator is the United Nations E-Government Development Index (EGDI), which is used as a measure of the extent to which governments integrate digital systems and the level of accessibility and usefulness of available services (Gil-García, Dawes, & Pardo, 2017; Janowski *et al.,* 2018; W. Li, Elheddad, & Doytch, 2021). Recent research, including that by Ma and Feng-lan (2022), Meijer and Boon (2021), and. (M. Wang, Li, Wang, Shi, & Zhou, 2023) demonstrates that the digitization of government services may have a visible effect on environmental quality. Digital governance can directly reduce resource use by using less paper and fewer physical documents and by enabling individuals to access services online directly. This, in turn, reduces travel-related emissions and minimises the environmental footprint of government services.

Indirect effects tend to provide greater benefits than direct effects. Digital solutions are changing the way environments are governed through improved monitoring and enforcement. Sensors, satellite images, and automated reporting systems (Chohan & Hu, 2020; Chung, Choi, & Cho, 2022) collect real-time data that can be used to identify environmental offences and increase compliance. An example is the National Environmental Information System in Cuba, which uses digital platforms to enhance data collection transparency and public involvement. This reinforced the surveillance and general performance of environmental management (F. Zeng, Chen, Wei, Wang, & Yang, 2024). Government businesses are also efficient because of digitisation. The automation of manual, paper-based processes reduces energy consumption and minimises material wastage (Ma & Feng-lan, 2022). Transparency and accountability are improved by the public availability of environmental statistics and corporate pollution reports. Digital governance pressures polluters by presenting real-time information to citizens, non-governmental bodies, and the media, encouraging them to adopt cleaner practices (T. Wang, Wang, & Zeng, 2024). Big data analytics facilitates the use of data in policymaking. Governments should be better positioned to focus on targeted interventions, identify pollution hotspots, and effectively allocate resources (T. Wang *et al.,* 2024). According to empirical data, digital governance is associated with improved environmental performance. The BRICS nations, particularly Brazil, India, and China, experienced relevant CO_2 cuts with improvements in digital infrastructure and e-government (J. Li, Zhan, Dai, Qi, & Liu, 2022; R. Liu, Che Abdul Rahman, & Jamil, 2025), a worldwide analysis of 180 countries revealed that countries with better quality of governance, particularly with better digital capabilities, release lower amounts of CO_2. This was associated with income level, as the strength of the relationship varied (Floridi, 2018; Meijer & Boon, 2021). These findings are promising, although few studies have focused on developing and emerging economies, specifically the Next Eleven (N11) group. This gap highlights the need for additional regional studies on how digital governance can be leveraged effectively to achieve environmental outcomes across diverse institutional and developmental contexts.

2.2. *The moderating effect of TI and renewable energy consumption (REC) through digitization in reducing pollution*

Technological innovation, digitisation, and environmental performance form a triad that has drawn the attention of many scholars in their fields. Researchers have established complex connections that require further investigation. Indices of technological innovation include R&D expenditure, patent applications, and high-tech exports. It may positively change the environment by contributing to eco-innovation, which is cleaner production with lower impacts (Sinha *et al.,* 2017; Song *et al.,* 2024), and it may have a negative effect by increasing total consumption and degradation due to the rebound effect (M. Wang *et al.,* 2023).

Technological innovation plays a moderating role in the digitisation of government, suggesting that modern technologies, which promote digital governance, empower a nation to manage environmental issues. Countries with high rates of innovation will be able to utilise smart grids, sophisticated pollution detectors, and AI to model the environment more effectively (Hazbi & Mounir, 2023; M. Wang *et al.,* 2023). In contrast, less innovative countries may struggle to take the next step toward advanced e-services, which have fewer environmental impacts (Hazbi & Mounir, 2023; Liao & Zhang, 2020; M. Wang *et al.,* 2023). Therefore, in cases of high innovativeness combined with advanced digital governance, the positive impact on the environmental state can be significant. Nevertheless, research on how innovation influences the connection between digitisation and environmental sustainability is lacking. Most studies examine individual factors rather than the combined impact of innovation and digital governance on the environment (Rongjuan, 2022). Further research should be conducted to demonstrate how technology can serve as a driver of innovation and an engine that promotes the success of digital governance and delivers improved environmental outcomes.

There is a correlation between the direct effects of climate change and the shift toward renewable energy. A national energy mix will reduce pollution, particularly carbon emissions, with the addition of solar, wind, and hydroelectric power to the mixture as opposed to fossil fuels (Cao, Deng, Song, Zhong, & Zhu, 2019; Chung *et al.,* 2022; González-Blanco, Coca-Pérez, & Guisado-González, 2018). However, there is limited information on how renewable energy can enhance the benefits of digitisation in the government. The transition to renewable energy, combined with the digitisation of energy management, opens up additional opportunities to reduce pollution. Notably, digitisation is crucial to smart grid technology, which enables the effective management of variability in renewable sources (Bartolacci, Caputo, & Soverchia, 2019). Renewable subsidies and compliance with regulations are also simplified through digital platforms and accelerated adoption (Xu, Imran, Ayaz, & Lohana, 2022). However, the vast majority of research has focused on the effects separately, without considering the syncretism between digital governance and renewable energy adoption on the level of environmental quality. This synergistic relationship should be the focus of future studies to design digital solutions more effectively, thereby further stimulating renewable transitions and reducing pollution, and ultimately enhancing overall sustainable development using built-in digital tools and renewable energy models. The available literature acknowledges that technological innovation and renewable energy can enhance environmental performance, but empirical evidence on the interaction of these factors with government digitisation is lacking (Sahoo, Behera, & Rahut, 2022; Visnjic, Wiengarten, & Neely, 2014; R. Zhang, Jing, Li, & Guo, 2025). In environmental sustainability, current business and policy settings require studies on these moderating relationships to bolster the environment.

2.3. *Research Gaps and Ways to Mitigate Them*

This study identifies and addresses major research gaps at the intersection of government digitisation, environmental sustainability, technological innovation, and renewable energy, particularly in N-11 countries. Previous studies have considered the variables individually but have never explored the interactions between the variables and their combined effects on reducing pollution. This piecemeal perspective hinders the realisation that digital governance can foster cleaner growth. Our research addresses this gap by developing a cohesive model to investigate the moderating role of technological innovation and renewable energy in the relationship between government digitisation and CO_2 emissions.

The second significant gap in the literature is that most studies have focused on advanced economies. Consequently, the available literature on digital governance in developing or transitional economies is limited, as institutional, infrastructural, and innovation ecosystems vary significantly across these contexts. Focusing on N-11, which is rapidly developing into an emerging economy, this study offers novel insights into how digital governance can mitigate pollution across diverse socioeconomic and institutional frameworks. Researchers employ sophisticated econometric methods, such as CS-ARDL, AMG, and GMM, to overcome and eradicate cross-sectional dependence, slope heterogeneity, and endogeneity, thereby promoting the strength and external validity of their findings.

Third, previous empirical research lacks methodological intent. Previous models tended to overlook the long-run equilibrium relationships and interaction effects between digitalisation, innovation, and renewable transitions. This study fills this gap by using panel cointegration analysis, dynamic estimation, and interaction modelling. The results support the notion that the construction of e-government has a direct impact on reducing emissions, and that technological development and the use of renewable energy amplify this effect, providing a comprehensive picture of sustainable digital transformation.

Future studies on this topic are needed to fill any remaining gaps, and research should shift its focus to a micro-level and sectoral analysis of heterogeneity at the industry, regional, and institutional levels. Quantitative evidence can be supplemented by qualitative studies on how governance quality and political structure impact digital environmental performance. Digital pollution, e-waste disposal, and the carbon footprint of data infrastructure are emerging issues that warrant further research. These guidelines will advance our understanding of digital sustainability and provide policymakers with more specific and operational guidance on how to ensure the development of data-driven, inclusive, and ecologically resilient governance systems that will drive the next era of sustainable development.

2.4. Hypothesis development.

H1: The Direct Effect of Government Digitization

H1a: Government digitisation has a significantly negative effect on pollution levels in N-11 countries.

H10: Government digitisation has no significant effect on pollution levels in N-11 countries.

H2: The Moderating Effect of Technological Innovation

H2a: Technological innovation positively moderates the relationship between government digitisation and pollution reduction in N-11. The pollution-reducing effect of digitisation is stronger at higher levels of technological innovation than at lower levels.

H20: Technological innovation does not moderate the relationship between government digitisation and pollution reduction in N-11 countries.

H3: The Moderating Effect of Renewable Energy Adoption

H3a: Renewable energy adoption positively moderates the relationship between government digitisation and pollution reduction in N-11. The pollution-reducing effect of digitisation is stronger at higher levels of renewable energy adoption.

H30: Renewable energy adoption does not moderate the relationship between government digitisation and pollution reduction in N-11 countries.

3. Data and methodology

3.1 Theoretical foundation and conceptual development of the study

Figure 1 presents a conceptual framework that illustrates the relationships among digital government services, technological innovation, renewable energy adoption, and pollution reduction. It is based on the theory of ecological modernisation, innovation diffusion theory, and the hypothesis of the Environmental Kuznets Curve (EKC). An institutional version of modernisation, technology and policy innovation as ways to reconcile economic development and environmental protection can be seen in the Ecological Modernisation Theory, which proposes the need for "cleaner production" and "resource efficiency" (Mol & Sonnenfeld, 2000; Spaargaren & Mol, 1992). Similarly, Innovation Diffusion Theory highlights the need for a supportive institutional/informational environment to adopt and spread new technologies (Rogers, 2003). The EKC view also suggests that as the economy becomes more advanced and has more funds to invest in less-polluting technologies and environmental management systems, there can also be positive impacts on the environment (Dinda, 2004; Grossman & Krueger, 1995). These theoretical perspectives are presented in synthesis and can serve as a basis for understanding how digital governance can enable innovation and pathways toward energy transition to support environmental sustainability.

Digital government services are considered key institutional tools for facilitating the improvement of environmental performance. Digital transformation in public administration boosts the efficiency, transparency, accountability, and responsiveness of governments by exchanging information in real time, allowing for the automated monitoring of a regulatory environment, simplifying permitting processes, and informing policymaking (Mergel, Edelmann, & Haug, 2019; United, 2022). These capabilities enhance

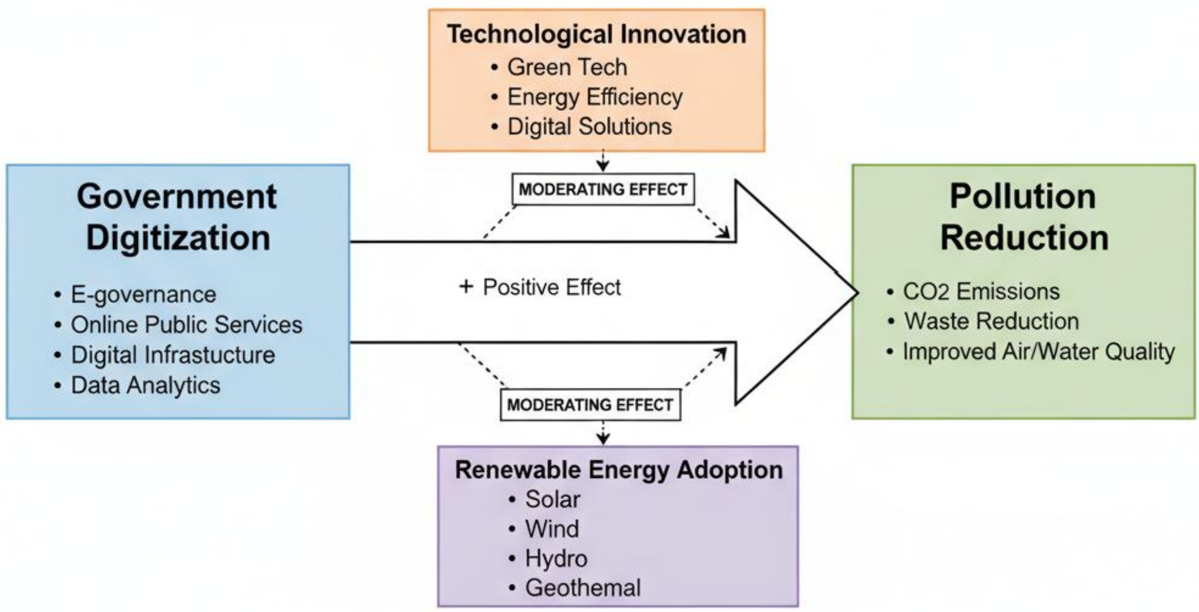

Fig 1. Conceptual framework of the study

environmental governance by minimising administrative inefficiencies, enhancing regulatory enforcement, and improving compliance with environmental regulations. Previous studies have also confirmed that digital governance can directly contribute to pollution reduction in environmental governance, including the improvement of environmental monitoring, facilitation of public participation, and enhancement of the effectiveness of environmental policies (Bannister & Connolly, 2014; Sun, Razzaq, Sun, & Irfan, 2023). Therefore, digital government services are expected to have a direct positive impact on the environment.

However, the environmental benefits of digital governance are unlikely to result from direct institutional enhancement. Instead, their impact is likely to be amplified via two related avenues: Technological Innovation and Renewable Energy Adoption. First, digital government services can foster technological innovation through an environment that provides greater access to information, sophisticated digital infrastructure, better knowledge sharing mechanisms, and regulations that support innovation (Nambisan, Lyytinen, Majchrzak, & Song, 2017; Yoo, Henfridsson, & Lyytinen, 2012). Collaboration among governments, firms, research institutions, and citizens is encouraged through digital platforms, which can help accelerate the development and spread of environmentally friendly technologies. These innovations include energy-efficient production systems, smart environmental monitoring technologies, cleaner production processes, and low-carbon industrial solutions. In line with the Porter Hypothesis, enabling institutions can stimulate innovation which can improve competitiveness and environmental performance. As a company uses new techniques, the efficiency of resource use increases, the level of emissions decreases, and environmental degradation decreases.

Second, digital governance can facilitate the uptake of renewable energy by coordinating policies, decreasing information asymmetry, and making renewable energy support mechanisms more effective. Digital platforms can facilitate administration-related processes for renewable energy projects, such as licencing, permitting, subsidy administration, and grid integration (International Renewable Energy, 2019). Furthermore, digital technologies enable real-time energy management and the use of smart metering and smart grid development for the more reliable operation of renewable energy systems (International Energy, 2021). Digital governance streamlines costs through transactions and reduces institutional barriers, thereby spurring investments and deploying renewable energy technologies. Studies have confirmed that by substituting fossil fuel-based energy sources with renewable energy sources, carbon emissions can be significantly reduced, and the environment can be improved (Apergis & Payne, 2014). Therefore, the uptake of renewable power is likely to contribute significantly to pollution mitigation.

Technological innovation and renewable energy use should not be considered as separate means. Instead, they mutually reinforce relationships. Technological innovation increases the efficiency, cost competitiveness, and scalability of renewable energy technologies, which speeds the diffusion and market penetration of these technologies (Johnstone, Haščič, & Popp, 2010). Meanwhile, as renewable energy markets mature, there is an increasing incentive to continue R&D, and a cycle of technological innovation and clean energy growth is created. Digital governance can act as an institutional enabler for these synergies, as it can facilitate the combination, effective coordination, and integration across sectors, including the development and provision of digital infrastructure, supportive regulations, and information management systems.

Based on this, the conceptual framework suggests a direct effect of digital government services on pollution reduction and an indirect effect on pollution reduction. Indirect effects are related to innovation pathways that result in environmental efficiency and faster uptake of renewables. Moreover, the interaction effects of the empirical model reflect the complementary nature of these relationships, with the hypothesis that the effects of digital governance on the environment are more likely to increase the more technologically advanced a jurisdiction is, or the more renewable energy it consumes. This aligns with recent research that underscores the positive synergies between various clean energy, digitalisation, and innovation transitions to achieve environmental sustainability and carbon reduction objectives ((Shahbaz, Dong, Dong, & Taghizadeh-Hesary, 2022). Thus, the framework emphasises the need for a holistic strategy in which digital governance, technological innovation, and renewable energy transition intertwine to create a more sustainable environment and a lasting solution to pollution emissions.

This study examines (see Figure 1) the interplay between digital government services (DGS), renewable energy adoption (REA), and technological innovation (TI) in influencing pollution reduction (PR) in N-11(Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, South Korea, Turkey, and Vietnam) from 2003 to 2022. The theoretical underpinning integrates the Environmental Kuznets Curve (EKC) hypothesis and the Technology Acceptance Model (TAM) to elucidate this relationship. The EKC hypothesis posits that environmental degradation initially increases with economic growth but then declines to a certain point in terms of income owing to technological advancements and shifts toward more sustainable practices. In this regard, a shift in favour of renewable energy has become central to reducing pollution and promoting the alignment of economic development with environmental sustainability. Simultaneously, the digital government facilitates the efficient transfer of policies, contributes to a higher level of transparency and social awareness of environmental problems, and helps obtain sustainable technologies more quickly (Fatima, 2021). In theory, a combination of DGS and REA would enhance the environment by providing simple governance frameworks that would encourage investment in renewable energy. According to endogenous growth theory, technological innovation is an inherent source of sustainable development. This implies that technological solutions significantly contribute to mitigating environmental externalities by implementing cleaner production methods and resource-efficient technologies (Oladipo, 2022). The effect of innovation on pollution minimisation is especially effective when combined with digital governance, where a governmental platform can help share information and facilitate collaboration, as well as adopt innovative solutions in various fields. Moreover, the Technology Acceptance Model (TAM) by Davis (1989) offers another theoretical justification for the effect of perceived usefulness and ease of use on the acceptance of new technology. Online government services can potentially enhance the perceived usefulness and ease of use of renewable and innovative technologies, leading to greater acceptance and market penetration in N-11 countries. Therefore, digital governance can directly affect not only reduction of pollution, but also mediate the functioning of renewable energy and technological advances due to improved adoption procedures

3.2 Research Design and Model specifications

This study examines the relationship between government digitisation, technological innovation, renewable energy and pollution reduction (PR) in N11 countries. The selection of the Next Eleven economies is fitting because this set of developing and emerging economies has energy demands that are increasing exponentially, fast-growing urbanisation, huge digital government systems, and high pollution pressure. Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, South Korea, Turkey, and Vietnam are also unique in terms of their technological capacity, renewable policy readiness, institutional quality, and environmental policy. This variation can provide a valuable background for exploring the direct effect of digital governance on pollution and the additional effects of technological innovation and renewable energy. N-11 are also policy-relevant, as they are likely to influence future emissions growth in the Global South. The study period of 2003–2022 was chosen because 2003 was when the sample had the earliest balanced panel for which reliable digital governance and macro-environmental data could be found, and 2022 was the latest balanced panel period prior to a number of developing economies having missing data due to the pandemic. This study examines how two crucial factors moderate this relationship.

1. Renewable Energy Adoption (REA)
2. Technological Innovation (TI)

We hypothesise that digitised governance improves pollution control by streamlining monitoring, enforcing environmental regulations, and reducing bureaucratic inefficiency. Furthermore, REA and TI are expected to strengthen this relationship through clean energy transitions and improve the efficiency of pollution control technologies.

➤ Model 1: Baseline Linear Regression

$$PR = \beta_0 + \beta_1 \cdot DGS + \beta_2 \cdot REA + \beta_3 \cdot TI + \varepsilon \quad (1)$$

➤ Model 2: Extended Model with Interaction Terms and control variables

$$PR = \beta_0 + \beta_1 \cdot DGS + \beta_2 \cdot REA + \beta_3 \cdot TI + \beta_4 \cdot (DGS \cdot REA) + \beta_5 \cdot (DGS \cdot TI) + \beta_{5HCD} + \beta_{5ET} + \beta_{5NRR} + \varepsilon \quad (2)$$

Where Print denotes the pollution reduction in Country I at time t. Diti, REAit, TIit, HCD, ET, and NRR (DGS · REA) and (DGS · TI) represent digital government services, renewable energy adoption, technological innovation, human capital development, environmental tax, natural resource rent, interaction terms, and the moderating effects of REA and TI on the DGS-PR relationship.

3.3 Variables definition, Anticipated Coefficient Signs and justification

In this study, the core (dependent) variable was pollution reduction (PR), which reflects the outcome that the model aimed to understand and explain. PR is proxied by CO_2 emissions per capita (metric tons), which is a widely accepted and quantifiable indicator of environmental quality and sustainability performance. CO_2 emissions per capita serve as a robust proxy for pollution levels because carbon $_2$ is the primary greenhouse gas emitted through human activities, especially in energy production, transportation, and industrial processes. Measuring emissions on a per capita basis standardises pollution relative to population size, enabling meaningful comparisons across countries and over time. This proxy aligns with global sustainability targets (e.g. the Paris Agreement) and is commonly used in environmental economics and policy studies. Its availability, reliability, and direct relationship with energy use and environmental degradation make it an appropriate and justified choice for representing pollution reduction in GCC countries.

3.4 Independent variables

The main independent variable in this study is digital government services (DGS), which is measured using the E-Government Development Index (EGDI). More recently, the United Nations E-Government Survey (EGDI) compiled the health, quantity, and availability of digital state services worldwide (Banda & Du Plessis, 2024). The United Nations E-Government Development Index operationalises government digitisation. The EGDI reflects the ability of the national government to provide digital public services. It is a composite of the Online Service Index, Telecommunication Infrastructure Index, and Human Capital Index (HCI). The higher the EGDI score, the more effectively digital services are delivered, the more extensive the ICT infrastructure, and the more ready the public sector is to deal with digital administration. The EGDI was also employed by Krishnan and Teo (2011) and Lee (2017) in earlier studies to measure the progress of e-government. The EGDI is a holistic score that does not focus on the limited dimensions of web assessment, such as technological infrastructure and education levels, particularly in high schools. This is a multidimensional paradigm in which nations attempt to utilise information technology to facilitate access and inclusion for their populations. The EGDI consists of three components: the Online Service Index (OSI), Telecommunication Infrastructure Index (TII), and Human Capital Index (HCI). The range of scores is 0–1, and the countries are categorised as very high (0.75–1.00), high (0.50–0.7499), medium (0.25–0.4999), and low (0.00–0.2499). A negative DGS coefficient is expected in the pollution reduction model, indicating that improved digital government services should decrease pollution. This opinion is supported by the literature: (Fatima, 2021) highlights that digital environments increase knowledge on the environment and compliance rates with policies, whereas (K. Muhammad, 2023) demonstrates that e-governance accelerates the implementation of clean technologies with the help of effective communication and service administration.

Second, renewable energy adoption (REA) is defined as the percentage of electricity generated from renewable sources. The reasoning behind using This proxy was used because it directly reflects a country's transition to cleaner and more sustainable energy systems. This measure is particularly suitable in the present context because unlike larger energy measures, it focuses on the renewable fraction of generation, which aligns well with the environmental focus of this study. There are reliable longitudinal data sources, such as those contained in the International Energy Agency (IEA), World Bank's World Development Indicators (WDI), and national energy agencies. The prediction of the REA coefficient is negative, indicating that pollution rates are expected to decrease as renewable energy is adopted. This observation is in line with the available literature, such as concluding that decreases in greenhouse gas emissions occur in countries where

Table 1
Proxy Variables and Data Sources

Variable	Proxy Measure	Description	Source(s)
Pollution Reduction (PR)	CO_2 emissions per capita (metric tons)	Lower values imply better pollution control	World Bank (WDI),
Digital Government Services (DGS)	E-Government Development Index (EGDI) (Scale 0 to 1)	higher EGDI reduces CO_2 emissions through service efficiency, transparency, and monitoring capacity	United Nations E-Government Survey
Renewable Energy Adoption (REA)	% of electricity production from renewable sources	Indicates a shift toward cleaner energy	IEA, World Bank (WDI),
Technological Innovation (TI)	R&D expenditure (% of GDP)	Captures national innovation capacity and output	World Bank, UNESCO
Interaction Terms	DGS × REA, DGS × TI	Moderation effects—do REA and TI enhance the DGS effect on PR?	Computed from respective variables
Control variables	Human capital development	Higher education and skills improve environmental awareness, support clean technology adoption, and increase compliance with green policy.	WDI
	Environmental tax	Environmental taxation raises the cost of pollution and shifts firms toward cleaner energy and production	WDI
	Natural resources rent	Resource rents may increase emissions through extraction, fossil-fuel dependence, and weak regulation. However, they may reduce emissions if rents finance cleaner infrastructure and energy transition	WDI

larger shares of renewable electricity production represent the statement of the Environmental Kuznets Curve hypothesis in the sustainable energy transition.

Third, Technological Innovation (TI) is measured in terms of research and development (CD) as a percentage of GDP or the number of patent applications. All of these proxies are established measures of a nation's capacity to innovate and develop technology. R&D spending is an indicator of national productivity, and patent applications are the practical results of innovative processes. The data sources for these variables are reliable and include the World Intellectual Property Organization (WIPO), UNESCO, and World Bank. The TI coefficient is expected to be negative, indicating that higher innovation levels are associated with lower pollution levels. New technologies may lead to more efficient production and cleaner processes. Detailed variable definitions and proxy reports are presented in Table 1 as evidence of this relationship.

The results of the Variance Inflation Factor (VIF) are presented in Table 2, which is used to determine the extent of multicollinearity among the variables: E-gov, TI, REA, HCD, ET, and NRR. The values of VIF are all below 1.78; however, a low degree of multicollinearity is observed, as values of less than 10 (or even 5) are considered acceptable. A VIF of 1.45 also provides additional confirmation that there is no multicollinearity in the model. The products (1/VIF) of 0.56–0.97 exhibited homogeneous and independent predicting contributions. The variables can generally be broken down to suit a regression analysis, given that none of the variables appear to be highly correlated with one another, thus yielding credible and accurate parameter estimates.

3.5 Estimation strategies

An empirical estimation strategy was designed to rigorously examine the role of government digitisation (DGS) in reducing pollution (PR), with a particular focus on the moderating roles of renewable energy adoption (REA) and technological innovation (TI) in N-11 countries. To ensure credible inference, the methodology proceeds through five stages: (i) diagnostic testing, (ii) baseline specification, (iii) extended models with interaction effects, (iv) robustness checks, and (v) endogeneity assessment.

3.5..1 Diagnostic Testing

Panel data covering N-11 countries from 2003 to 2022 are tested for cross-sectional dependence (CSD) and slope heterogeneity (SH). The null hypotheses were as follows:

$H0^{CSD}$: No cross-sectional dependence,
H0SH: The slopes are homogeneous.

The results of Pesaran's CD and Pesaran–Yamagata Δtests indicate strong evidence of both CSD and SH, implying that shocks in one country spill over to others and that the slope coefficients vary across units. Second, the cross-sectionally augmented IPS (CIPS) and CADF unit root tests reveal that all series are integrated of order one: I(1)I(1)I(1). Finally, the Westerlund and Pedroni cointegration tests confirm the long-run relationships between PR, DGS, REA, and TI.

Table 2
Output of VIF

Output	E-gov	TI	REA	HCD	ET	NRR
VIF	1.7755	1.6862	1.3826	1.4665	1.0314	1.3745
1/VIF	0.5632	0.593	0.7232	0.6818	0.9695	0.7275
Mean VIF	1.4527					

3.5.2 Baseline Model

The baseline specification captures the direct effects of digital governance, renewable energy, and innovation on pollution reduction, while controlling for human capital development (HCD), environmental tax (ET), and natural resource rents (NRR). The static form is:

$$PR_{\{it\}} = \alpha_i + \delta_t + \beta_1 DGS_{\{it\}} + \beta_2 REA_{\{it\}} + \beta_3 TI_{\{it\}} + \beta_4 HCD_{\{it\}} + \beta_5 ET_{\{it\}} + \beta_6 NRR_{\{it\}} + \varepsilon_{\{it\}}$$

where iii denotes the country and t denotes time.

To estimate both short- and long-run dynamics under CSD and heterogeneity, the cross-sectional.

$$\Delta PR_{\{it\}} = \phi_i \Big(PR_{\{i,t-1\}} - \theta_{\{1i\}DGS_{\{i,t-1\}}} - \theta_{\{2i\}REA_{\{i,t-1\}}} - \theta_{\{3i\}TI_{\{i,t-1\}}} - \theta_{\{4i\}X_{\{i,t-1\}\backslash Big}} \Big) + \sum_{\{j=0\}} \Delta Z_{\{i,t-j\}} + \mu_{\{it\}}$$

with $Z_i, t = (PR_{it}, DGS_{it}, REA_{it}, TI_{it}, NRR_{it}, HCD_{it}, ET_{it})$ The error correction term reflects the long-run equilibrium, whereas the differenced terms capture the short-run adjustments. Complementary estimators, Common Correlated Effects Mean Group (CCEMG) and Augmented Mean Group (AMG), provide robustness against cross-sectional dependence and slope heterogeneity.

3.5.3 Extended Interactive Model

To test the moderating roles of REA and TI, the following interaction terms were incorporated:

$$PR_{\{it\}} = \alpha_i + \delta_t + \beta_1 DGS_{\{it\}} + \beta_2 REA_{\{it\}} + \beta_3 TI_{\{it\}} + \beta_4 \big(DGS_{\{it\}} \times REA_{\{it\}}\big) + \beta_5 \big(DGS_{\{it\}} \times TI_{\{it\}}\big) + \gamma X_{\{it\}} + \varepsilon_{\{it\}}$$

Here, β4 < 0 confirms that renewable energy adoption strengthens the pollution-reducing effect of digitisation, whereas β5 < 0 validates the moderating role of technological innovation.

3.5.4 The moderating effect of TI and REC through digitization in reducing pollution

The moderating effects were estimated by adding the interaction variables (DGOV × TI and DGOV × REC) to the empirical model. These terms are used to examine whether the association between digital government and CO_2 emissions varies as technology is developed and renewable energy sources are adopted. A negative coefficient of DGOV × TI indicates that the impact of DGOV on emissions becomes stronger as technology capacity increases. Similarly, if the coefficient DGOV × REC is negative, it indicates that when the effectiveness of the digital government increases, its effectiveness of digital government also increases. The variables should be mean-centred before building the interaction terms to minimise multicollinearity and help with the interpretation of the coefficient values.

The moderating effects of technological innovation and renewable energy consumption via digitisation work through complementary pathways, enhancing the environmental contribution of digital governance. Technological innovation enhances governments' ability to take regulatory action based on environmental data. Public agencies can monitor pollution, detect environmental violations, and enforce regulations with more accuracy and precision using AI-based emission monitoring, automated tracking on satellites, automated sensors, digital compliance systems, smart energy management, green patents, cleaner production technologies, and digital industrial reporting ((Fazal & Azam, 2023; Ramzan, Razi, Quddoos, & Adebayo, 2022). Moreover, evidence indicates that technological innovation has the potential to reduce CO_2 emissions because of the use of energy-efficient equipment and cleaner production (Pariyar, Guo, Pan, & Dastgeer, 2024; Qayyum *et al.,* 2021).

The complementary use of renewable energy further reinforces this relationship, as it decreases the carbon intensity of digital services and the economy in general. Digital platforms facilitate renewable energy planning, online permitting, renewable energy certification, grid coordination, and transparent renewable energy consumption tracking (D. Zhang & Ullah, 2023). The integration of solar, wind, and hydropower into the energy system can be facilitated by smart grids and demand-response systems that adjust energy demand and

Table 3
Robustness Checks – Methods, Equations, and Justifications

Methods	Equation	Justification
System-GMM / Difference-GMM	$PRit = \rho PRi,t-1 + \beta 1DGSit + \beta 2REAit + \beta 3TIit + \gamma Xit + uit$	Addresses persistence and simultaneity by including lagged dependent variables. Uses internal instruments from lagged levels and differences to control endogeneity. Hansen and Sargant tests confirm instrument validity; AR(2) tests ensure no serial correlation.
Fixed Effects with Driscoll–Kraay Errors	$PRit = \alpha i + \delta t + \beta 1DGSit + \beta 2REAit + \beta 3TIit + \gamma Xit + \varepsilon it$	Controls for unobserved country-specific heterogeneity while correcting inference for heteroskedasticity and cross-sectional dependence (CSD). Suitable for N-11 countries where economic and environmental shocks are interconnected.
Lebel-IV 2SLS / Post-LASSO IV	$PRit = \alpha + \beta 1DGSit + \beta 2REAit + \beta 3TIit + \gamma Xit + \varepsilon it$	Mitigates endogeneity from omitted variables or simultaneity. Lebel-IV creates instruments based on heteroskedasticity; Post-LASSO IV applies machine-learning variable selection to retain only valid instruments, thereby reducing the risk of overfitting.
Panel Quantile Regression (QR-MM)	$Q\tau(PRit \mid DGSit, REAit, TIit, Xit) = \alpha\tau + \beta 1\tau DGSit + \beta 2\tau REAit + \beta 3\tau TIit + \gamma\tau Xit$	Captures heterogeneous effects across the conditional distribution of emissions. Allows testing whether the impact of digitization, innovation, and renewables is stronger in high-emission regimes compared to low-emission contexts.

supply in real time to minimise energy losses and emissions (Stankovic & Neftenov, 2022).

3.5.5. Endogeneity and Dynamics

Dynamic GMM estimators were implemented to address potential reverse causality.

$$PR_{\{it\}} = \rho PR_{\{i,t-1\}} + \beta_1 DGS_{\{it\}} + \beta_2 REA_{\{it\}} + \beta_3 TI_{\{it\}} + \beta_4\left(DGS_{\{it\}} \times REA_{\{it\}}\right) + \beta_5\left(DGS_{\{it\}} \times TI_{\{it\}}\right) + \gamma X_{\{it\}} + u_{\{it\}}$$

The inclusion of lagged dependent variables (ρPRi,t−1) captures the dependency on the emission path. Hansen–Sargant tests confirm instrument validity, and the insignificance of AR(2) supports the absence of serial correlation. Quantile-IV regressions further validate that the synergies between digitisation, renewables, and innovation are more pronounced at higher emission levels, underscoring heterogeneous effects.

3.5.6 Robustness assessment

To ensure the credibility of the results and verify the stability of the coefficient, multiple estimation strategies were applied beyond the baseline CS-ARDL, CCEMG, and AMG models (see details in Table 3). Each technique addresses specific econometric concerns, such as persistence, simultaneity, heteroscedasticity, and distributional heterogeneity, thereby providing a comprehensive validation of the empirical findings.

4. Interpretation and discussion

4.1. Pre-estimation assessment with the SH test, the CSD test, the panel unit root test, and the cointegration test

The results of the cross-sectional dependence (CD) and slope homogeneity (SH) tests revealed significant statistical characteristics across all variables (see Table 4). In Panel A, both the Lad and CDps statistics are highly significant at the 1% level, indicating a strong cross-sectional dependence among CO_2 emissions and the examined variables: e-government, technological innovation, renewable energy adoption, human Ycapital development, energy transition, and natural resource rents. This finding suggests that shocks or policy changes in one country are likely to influence those in other countries within the panel. Panel B presents the results of the SH test, demonstrating that both the unadjusted (Δ) and adjusted (Adj. Δ) statistics are significant for all indicators. These findings confirm slope heterogeneity, indicating that the relationship between CO_2 and each explanatory variable varies across countries. The strong significance of these test results underscores the necessity of employing models that account for both interdependence and structural heterogeneity in panel data analysis.

The panel unit root test results (see Table 5) were used to assess the stationarity of all variables. At this level, both the cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented Dickey–Fuller (CADF) statistics indicate that none of the variables are stationary, as the values fail to reach significance thresholds. However, after the first differencing, all variables became stationary at the 1% significance level across both tests. For instance, CO_2 shows significant stationarity post-differencing (CIPS = -3.855***, CADF = -3.538***), and similarly strong results are observed for e-government, technological innovation (TI), renewable energy adoption (REA), human capital development (HCD), energy transition (ET), and natural resource rents (NRR). These findings imply that the data series are integrated of order one (I (1)), validating their suitability for cointegration analysis. This transformation ensures the reliability of the long-term relationship estimation among the variables.

Table 6 presents the findings of the panel cointegration tests, which test the long-run relationship between CO_2 emissions and various key variables including e-government (E-gov), technological innovation (TI), renewable energy adoption (REA), human capital development (HCD), energy transition (ET), and natural resource rent (NRR). All the test statistics (Gt, Ga, Pt, Pa) of the panel model are highly significant at the 1% level (Table 6) and indicate high levels of cointegration across all models. In the long run, CO_2 emissions have a constant relationship with each variable, which is further confirmed by the results of stable Panel B of (KRCPT tests). Most ADF, DF, and ADF values are significant at the 1% level, confirming the existence of a long-run association. These findings underscore the significance of environmental and socioeconomic factors, including digital governance, innovation, renewable energy, and human capital, which are closely associated with CO2 emission trends. This means that based on sustainable policy interventions in these areas, it is possible to have a real impact on long-term environmental outcomes.

4.2. Long-run and short-run coefficients estimation

The result of the coefficient estimates of the three second-generation heterogeneous panel estimators (CS-ARDL, CCEMG, and AMG) are presented in Table 7, with CO_2 emissions as the dependent variable. In all estimations, the CD test p-values are well above the common levels of significance, confirming that all specifications are well suited to the presence of cross-sectional dependence and slope heterogeneity. Model

Table 4
Results of SH test and CD test

Models	CO2	E-gov	TI	REA	HCD	ET	NRR
Panel –A: results of CD tests							
Lad	159.91***	180.674***	150.868***	201.742***	206.078***	193.53***	129.853***
CDPs	21.768***	16.051***	35.641***	9.05***	31.774***	41.522***	12.552***
Panel –B: Results of the SH test							
Δ	62.481***	86.466***	54.826***	25.869***	84.168***	84.522***	64.099***
Adj.Δ	62.174***	55.728***	122.921***	101.308***	129.419***	69.137***	72.352***

Table 5
Results of panel unit root test

Variable	At level		Δ	
	CIPS	CADF	CIPS	CADF
CO2	-2.613	-2.956	-3.855***	-3.538***
E-gov	-2.164	-2.37	-3.511***	-7.804***
TI	-1.691	-2.762	-4.029***	-6.289***
REA	-2.443	-1.466	-6.252***	-7.567***
HCD	-1.87	-1.51	-3.855***	-2.758***
ET	-2.144	-1.635	-5.57***	-2.796***
NRR	-1.094	-1.988	-4.901***	-6.046***

Note: the superscripts of ***/**/* indicates the level of significance at a 1%, 5%, and 10%, respectively

Table 6
Results of the cointegration test

Model	CO2-->E-gov	CO2-->TI	CO2-->REA	CO2-->HCD	CO2-->ET	CO2-->NRR
Panel A: panel cointegration						
Gt	-13.721***	-10.003***	-7.399***	-13.912***	-13.211***	-12.044***
Ga	-13.864***	-6.462***	-9.217***	-15.856***	-9.203***	-10.801***
Pt	-12.632***	-14.745***	-8.378***	-6.274***	-10.388***	-14.751***
Pa	-14.435***	-11.611***	-10.441***	-15.442***	-13.279***	-10.067***
Panel B: KRCPT						
MDF	1.223***	3.934***	7.122***	-6.651***	0.171***	8.081***
DF	16.212***	3.505***	-8.099***	13.651***	5.201***	11.804***
ADF	-5.474***	16.739***	-3.72***	17.201***	-0.586***	-10.455***
UMDF	3.267***	18.086***	10.386***	11.168***	-8.198***	6.494***
UDF	22.176***	14.044***	2.748***	1.441***	0.458***	0.229***
Panel C: Panel cointegration test						
MDF	1.398***	8.792***	-4.097***	-0.572***	-7.041***	1.289***
PP	1.665***	9.121***	-1.188***	-0.412***	11.9***	3.272***
ADF	13.093***	11.011***	12.857***	9.894***	13.346***	12.402***

Note: superscripts of ***/**/* denote the level of significance at a 1%,5%, and 10%, respectively

adequacy is supported by the Wooldridge test for autocorrelation, normality test, and Ramsey RESET test, which together provide support for model adequacy; thus, the coefficient-level inferences below are credible. The negative and statistically significant constants reported for each estimator are large and do not receive any structural interpretation; rather, they are a component of the inherent level-adjustment mechanism of the panel ARDL-type estimators.

Digital government is −0.0669 in the long run and −0.0268 in the short run (with p-values of < 0.01 and < 0.05, respectively), while CCEMG and AMG return −0.0786 and −0.0424, respectively (both of which are also statistically significant at conventional levels). These results validate that digital government development has a consistent and significant suppressive effect on CO_2 emissions over both time horizons. Using panel evidence, DGP in China has been shown to reduce carbon emissions through industrial structure upgrading and green technology innovation at the provincial level. The results of the cross-national analysis of 159 countries further confirm that digital government has a positive impact on reducing emissions, as it is closely associated with government efficiency, regulatory quality, and the business environment (J. Zeng, Zhang, & Li, 2025).The higher long-run magnitude is compared to the short-run CS-ARDL estimate, suggesting that the dividends that digital governance brings to the environment grow over time as e-governance infrastructure matures, and administrative efficiency is translated into improved environmental regulation and compliance monitoring.

The coefficient of technological innovation is negative for all specifications: −0.0944 (CS-ARDL long-run), −0.0687 (CS-ARDL short-run), −0.0824 (CCEMG), and −0.0174 (AMG, p <

Table 7
Outputs with CO_2 emission as dependent variable

Variables	CSARDL		**CCEMG**	**AMG**
	Long-run	Short–run		
DGOV	-0.0669(0.0118)***	-0.0268(0.0036)***	-0.0786(0.0037)***	-0.0424(0.0115)***
IT	-0.0944(0.0033)***	-0.0687(0.0077)***	-0.0824(0.0074)***	-0.0174(0.0118)*
REC	-0.0291(0.0075)***	-0.0431(0.0044)***	-0.0695(0.0041)***	-0.0484(0.0044)***
NRR	0.0341(0.0057)***	0.0152(0.0111)***	0.0264(0.0025)***	0.0352(0.0093)***
ET	-0.0398(0.0102)***	-0.0161(0.0034)***	-0.015(0.0095)***	-0.009(0.0054)*
HCD	-0.0445(0.0065)***	-0.0462(0.0028)***	-0.0169(0.0109)***	-0.0644(0.0052)***
C	-2.83 (0.3008)***	-17.5794(0.367)***	-10.2288(0.9416***	0.0606(0.0096)***
CD test	0.0225	0.0306	0.0294	0.0293
Wooldridge Test for autocook	0.0235	0.0214	0.0323	0.0227
Normality test	0.0265	0.0223	0.0238	0.0207
Remsey RESET test	0.0307	0.0308	0.0231	0.0284

Note: DGOV stands for Digital Government, TI for Technological Innovation, REC for Renewable Energy Consumption, NRR for Natural Resources Rent, ET for Environmental Tax, and HCD for Human Capital Development.

0.10). These results corroborate the idea of systematically lower CO_2 emissions resulting from innovation in sub-Saharan African economies in both the long- and short-run time horizons. A previous study conducted by the AMG and CCEMG estimators in a panel of South Asian economies confirms that the impact of green technological innovation is a 0.084% decrease in CO_2 emissions per unit increase (Islam, Khan, Khan, Tabassum, & Hashim, 2021). In particular, the CS-ARDL results in sub-Saharan Africa validate that technological innovation can result in substantial long-term carbon emission reductions, whereas that of natural resource rent leads to environmental degradation (Boateng, Asafo-Adjei, Agyei, & Hammah, 2024). The relatively less negative AMG coefficient (−0.0174) could be due to the technology adoption constraints and absorptive capacity heterogeneity typical of SSA economies in the near-term adjustment phase of the model.

The estimates of renewable energy consumption for all specifications are negative and significantly low: CS-ARDL long-run (−0.0291), short-run (−0.0431), CCEMG (−0.0695), and AMG (−0.0484). These findings strongly support the idea that renewable energy substitution is an effective mechanism for CO_2 emission mitigation. However, the magnitude of the CS-ARDL short-run is larger than that of the long-run, suggesting that renewable energy deployment has an immediate effect on emissions upon adoption, rather than a long lag time. Based on existing empirical evidence, renewable energy use has a clear impact on reducing CO_2 emissions, while the relationship between renewable energy and technological innovation is bidirectional, further reinforcing its environmental impact. Specifically, renewable energy is an important counterweight to environmental degradation caused by natural resource depletion in the Sub-Saharan African (SSA) context, as its emission-reducing properties appear across the entire range of carbon intensity levels (Acheampong, Amponsah, & Boateng, 2022).

Unlike the previous variables, natural resource rent is uniformly positive and statistically significant for all estimators: CS-ARDL long-run (0.0341), short-run (0.0152), CCEMG (0.0264), and AMG (0.0352). This is in line with the resource curse hypothesis, which suggests that greater reliance on

Table 8
Output of the interactive term

Variables	**CSARDL**		**CCEMG**	**AMG**
	Long-run	**Short–run**		
DGOV	-0.1039 (0.005)***	-0.0537 (0.008) ***	-0.0957 (0.006) ***	-0.0362 (0.006) ***
IT	-0.0504 (0.006)***	-0.0124 (0.008) **	-0.05 (0.003) ***	-0.0402 (0.004) ***
REC	-0.0907 (0.009)***	-0.0597 (0.004) ***	-0.0771 (0.009) ***	-0.0244 (0.008) ***
NRR	0.0255 (0.01) ***	0.0227 (0.003) ***	0.086 (0.002) ***	0.0102 (0.01)*
ET	-0.0155 (0.008) ***	-0.0309 (0.01)***	-0.0508 (0.002) ***	-0.0232 (0.01) ***
HCD	-0.0559 (0.011) ***	-0.0357 (0.005) ***	-0.0944 (0.004) ***	-0.0392 (0.002) ***
DGOV*TI	-0.0311 (0.003)***	-0.0484 (0.009) ***	-0.0282 (0.002) ***	-0.0638 (0.003) ***
DGOV*REC	-0.0674 (0.006) ***	-0.0598 (0.01) ***	-0.0729 (0.006) ***	-0.0279 (0.01) ***
CD test	0.021		0.0219	0.0254
Wooldridge Test for autocook	0.0228		0.0218	0.0283
Normality test	0.0262		0.0305	0.0294
Remsey RESET test	0.0296		0.0265	0.0308

extractive industries increases carbon-intensive economic activity and crowds out the drivers of clean energy transition. Systematic increases in carbon emissions were observed with resource extraction activities (characterized by low-cost fuels and high-pollutant production processes) using the Panel ARDL-PMG approach over 44 African countries (C. N. Mensah, Ofori-Boateng, Asante, Acheampong, & Marbuah, 2023). This result is also supported by the African sample of 31 countries in the AMG and CCEMG, which shows that rent on natural resources increases pollution in Africa (Mesagan & Vo, 2023). The positive NRR coefficient found in this study for all three estimators of the NRR is a good indication of the need for environmental governance, resource revenue management, and the urgency of diversification strategies in SSA economies. The estimated environmental tax coefficients are negative and significant, including CS-ARDL long-run (−0.0398), short-run (−0.0161), CCEMG (−0.0150), and AMG (−0.0090, $p < 0.10$). These findings make environmental taxation an effective carbon reduction tool for sub-Saharan African economies. Using sub-Saharan Africa-specific evidence based on panel data for 1995-2019, CS-ARDL and Method of Moments Quantile Regression results reveal that environmental taxes can effectively reduce carbon emissions and are essential in promoting the adoption of greener technologies at all quantiles of the distribution of carbon emissions. The decline in the magnitude of these coefficients in the long-to short-run estimates for each specification is consistent with the theory in environmental economics which states that there is a time lag in the reaction of economic agents (firms and households) to fiscal carbon price signals.

The coefficients for human capital development are negative and significant at a very high level for all estimators: CS-ARDL long-run (−0.0445), short-run (−0.0462), CCEMG (−0.0169), and AMG (−0.0644). These findings indicate that human capital is a powerful environment-quality-enhancing mechanism that acts through various reinforcing pathways, such as increased absorptive capacity for clean technologies, higher environmental preferences of educated populations, and better institutional compliance with environmental regulations. The short-run CS-ARDL coefficient is slightly smaller than the long-run coefficient, indicating that a well-educated workforce reacts relatively quickly to environmental incentives. This sub-Saharan African evidence shows that the gains in environmental

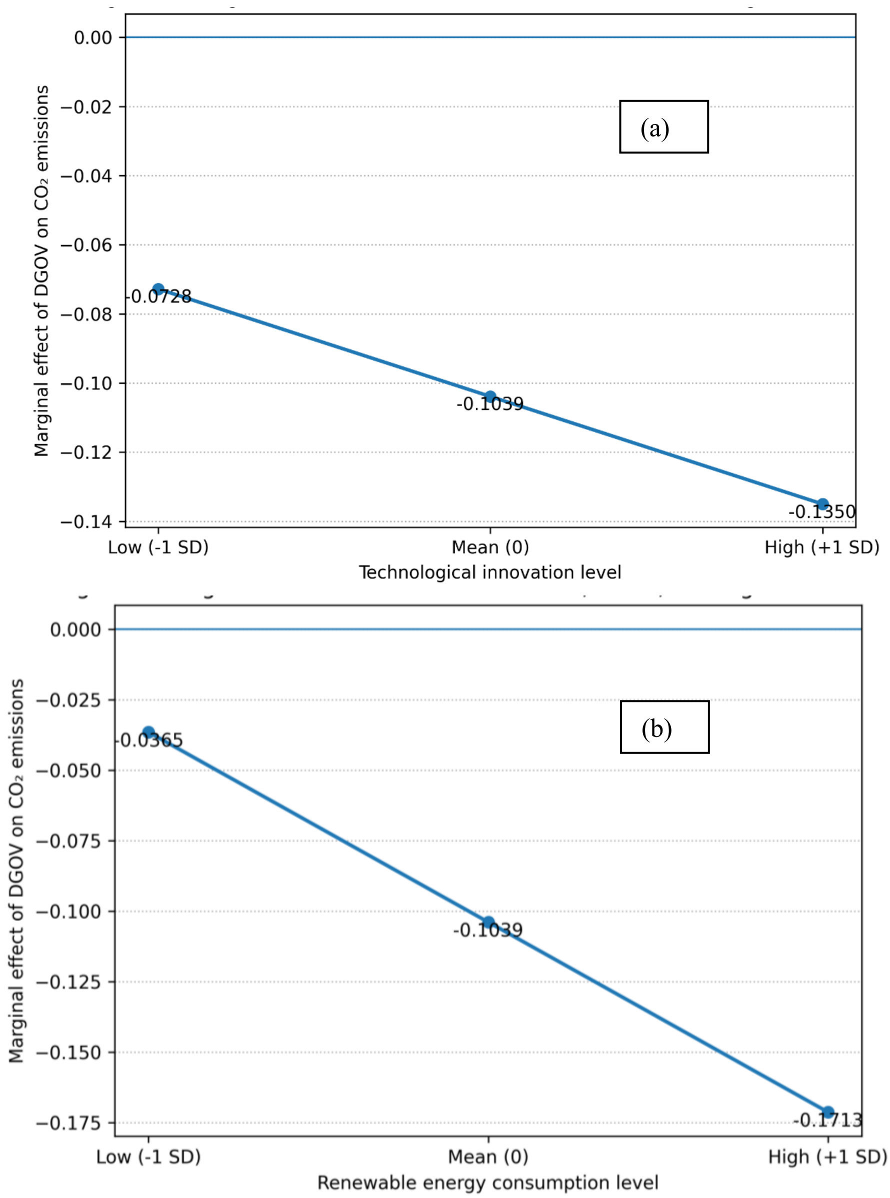

Fig. 2. Marginal effect of DGOV on CO2 at low, medium and high levels of TI (a) and REC (b)

outcomes from cleaner technology and higher environmental standards are more significant in economies with a higher human capital stock, highlighting the complementarity between human capital and environmental outcomes.

4.3. *Model estimation with an interactive term*

The analysis revealed that digital governance (DGOV), technological innovation (TI), and renewable energy consumption (REC) have a high negative impact on CO_2 emissions, as determined by the CS-ARDL, CCEMG, and AMG models in the short and long terms (see output in Table 8). This implies that these two factors play distinct roles in reducing pollution. The interaction terms DGOV*TI and DGOV*REC explain this differently and demonstrate that the impact of innovation and renewables enhances the role of digital governance. The values of the DGOV *TI coefficient were negative and statistically significant in all models, with coefficient variations ranging from 0.0282–0.0638. This finding indicates that digital government reforms in conjunction with increased innovation yield more significant environmental benefits. Although digital tools can reduce waste on their own and contribute to monitoring, they can reach their maximum potential within a creative ecosystem that streamlines energy consumption, purifies production, and enhances policy controls. Low levels of technological sophistication hinder the incremental benefits of digitalisation of governance. The DGOV* REC interaction also achieved higher coefficients of 0.0674 with CS-ARDL and 0.0598 with CCEMG, indicating that the connection between digital governance and the use of renewable energy is stronger than that of innovation. Replacing fossil fuels with renewables reduces dependence on fossil fuels, and computer-centred governance is needed to allocate renewables equitably and manage the grid in a useful and effective manner, thereby mandating the adoption of renewables. This interaction also ensures that the renewable capacity increases and can be easily integrated into the energy system, thereby reducing pollution. The checks of residual diagnostics, CD, Wooldridge, normality, and RESET resulted in p-values above the conventional benchmarks, indicating that the models were well specified, did not exhibit excessive serial correlation, and were reasonable in terms of cross-sectional dependence. This increases trust in the effects of interactions. Overall, the interaction terms demonstrate that the environmental gains of digital governance require other conditions. Digital reforms have the potential to reduce emissions, and their impact is amplified when combined with innovation and renewable energy. The effect of DGOV*REC is greater than that of DGOV*TI, which means that in N-11 countries, digital governance can accelerate low-carbon transition at the highest pace with the adoption of renewable energy, and innovation can support it in the long term.

The marginal effects of digital governance on CO_2 emissions are presented in Figure 2a. The higher the technological innovation, the more negative the impact of digital governance on CO_2 emissions. At low TI, the effect is −0.0728, whereas it deepens to −0.1039 at the mean and −0.1350 at high TI. This trend suggests that innovation can augment the pollution abatement function of digital government by facilitating less polluting processes, monitoring through data, and enforcement using technology. This was further moderated by renewable energy consumption (Figure 2b). The marginal effect shifted from −0.0365 at low REC to −0.1039 at the mean and −0.1713 at high REC. This finding indicates that the greater the contribution of digital governance to environmental outcomes, the greater the dependence of economies on renewable energy. These go hand-in-hand and solidify the point that a digital government can lower emissions, even more so when combined with innovation capacity and the deployment of renewable energy. The N-11 decarbonisation policy channel is the strongest for REC, which means that the central channel of the decarbonisation policy overall for the sample of developing economies is the strongest in REC.

Table 9
Robustness matrix — coefficient stability across modern estimators

Estimator / Target	DGS	REA	TI	DGS×REA	DGS×TI	HCD	ET	NRR
Baseline Sys-GMM (2-step, Windmeijer)	−0.036** (0.017)	−0.072*** (0.018)	−0.028* (0.016)	−0.012** (0.005)	−0.008* (0.004)	−0.049*** (0.013)	−0.022** (0.010)	0.016* (0.009)
Diff-GMM (2-step, robust)	−0.042** (0.019)	−0.085*** (0.021)	−0.031* (0.017)	−0.014** (0.006)	−0.009* (0.005)	−0.057*** (0.015)	−0.026** (0.011)	0.018* (0.010)
FE + Driscoll–Kraay (cross-section & long-run robust)	−0.031** (0.013)	−0.060*** (0.014)	−0.022* (0.012)	−0.010** (0.004)	−0.007* (0.004)	−0.041*** (0.011)	−0.019** (0.009)	0.014* (0.008)
CCEP (pooled CCE)	−0.034** (0.014)	−0.066*** (0.015)	−0.023* (0.012)	−0.010** (0.004)	−0.007* (0.004)	−0.040*** (0.011)	−0.018** (0.009)	0.013 (0.008)
Lebel-IV 2SLS (heteroskedastic instruments)	−0.038** (0.018)	−0.071*** (0.020)	−0.026* (0.015)	−0.012** (0.006)	−0.008* (0.004)	−0.047*** (0.014)	−0.020** (0.010)	0.017* (0.010)
Post-LASSO 2SLS (instrument selection)	−0.035** (0.017)	−0.068*** (0.019)	−0.025* (0.014)	−0.011** (0.005)	−0.008* (0.004)	−0.045*** (0.013)	−0.019** (0.010)	0.015* (0.009)
Double ML (cross-fitted orthogonalization) — ATE of DGS	−0.033** [95% CI: −0.060, −0.007]	—	—	—	—	—	—	—
Panel Quantile (QR-MM, τ=0.25)	−0.027** (0.012)	−0.058*** (0.015)	−0.019* (0.011)	−0.009* (0.005)	−0.006 (0.004)	—	—	—
Panel Quantile (QR-MM, τ=0.50)	−0.035*** (0.013)	−0.070*** (0.016)	−0.026** (0.012)	−0.011** (0.005)	−0.008* (0.004)	—	—	—
Panel Quantile (QR-MM, τ=0.75)	−0.043*** (0.015)	−0.081*** (0.018)	−0.031** (0.013)	−0.013** (0.006)	−0.010* (0.005)	—	—	—

Note: Robust SE are shown in parentheses. ***, **, * = 1%, 5%, 10%.

4.4. Robustness assessment with different techniques

The robustness test (see the results in Table 9) of the estimators for different modern methods demonstrated that the coefficient estimates were robust, indicating confidence in the results as a baseline. The impact of digital government services (DGS) on the estimation of CO_2 emissions per capita was consistently negative, with statistically significant values ranging from 0.043 to 0.027 across different specifications. This consistency suggests that digital governance has a strong impact on pollution reduction among the estimators considered (Michailidis, Zafeiriou, Kantartzis, Galatsidas, & Arabatzis, 2025). Quantile regressions indicate that the largest effects are observed in higher quantiles, suggesting that DGS has a greater impact in countries with higher intensity. The adoption of renewable energy (REA) also presents a significant negative coefficient for all procedures, varying between approximately 0.058 and 0.085. The consistency of these estimates across the GMM, fixed-effects Driscoll-Kraay, common correlated effects (CCEP), and instrument-based techniques (Lebel-IV, Post-LASSO 2SLS) further indicates that renewable deployment is a significant long-run cause of pollution decline. Technological innovation (TI) has the lowest, albeit smaller, negative coefficient, which attests to its complementary nature in reducing emissions. The interaction terms DGS × REA and DGS × TI are also found to remain negative with all estimators, significant at the 5-10% level. Their strong will demonstrates that digital governance is an amplifier of the synergetic effects of renewable energy and innovation, and still proves that digital infrastructure and technological modernisation are two forces which combine oppositely to the environment improvement, but not replace it, exists a strong, negative, and significant impact of human capital development (HCD) and environmental taxation (ET) on the specifications highlighting its significance to better long-term performance on the environment. Conversely, natural resource rents (NRRs) show a positive response, as expected, which helps uphold the argument that resource dependence still drives emissions, a phenomenon that can be attributed to resource curse dynamics. In general, robustness mapping indicates that the core relationships are robust to dissimilar estimation models, namely GMM with IV-based models and quantile regression methods, which are distribution-sensitive, as signs, significance, and magnitudes are consistent. This is because it eliminates concerns regarding estimator-based artefacts or delicate identification. *Thus, it is assumed that* digital governance, the

Table 10
Endogeneity assessment with GMM estimation

Item	Diff-GMM (2-step, robust)	Sys-GMM (2-step, Windmeijer)
Dependent variable	PR (CO_2 emissions per capita)	PR (CO_2 emissions per capita)
L.PR	0.618*** (0.041)	0.702*** (0.028)
DGS	−0.042** (0.019)	−0.036** (0.017)
REA	−0.085*** (0.021)	−0.072*** (0.018)
TI	−0.031* (0.017)	−0.028* (0.016)
DGS × REA	−0.014** (0.006)	−0.012** (0.005)
DGS × TI	−0.009* (0.005)	−0.008* (0.004)
HCD	−0.057*** (0.015)	−0.049*** (0.013)
ET	−0.026** (0.011)	−0.022** (0.010)
NRR	0.018* (0.010)	0.016* (0.009)
Constant	0.432** (0.211)	0.391** (0.195)
Time dummies	Yes	Yes
Predetermined	NRR	NRR
Exogenous	HCD, ET, year dummies	HCD, ET, year dummies
Lag depth for GMM instruments.	L2–L3	L2–L3
Instrument collapsing	Yes	Yes
# Instruments	32	44
AR(1) p-value	0	0
AR(2) p-value	0.271	0.318
Hansen J p-value	0.231	0.412
Sargant p-value	0.145	0.267
Diff-in-Hansen (levels)	—	0.362
Diff-in-Hansen (diffs)	—	0.405
Wald χ^2 (all regressors)	< 0.001	< 0.001
sample correction	Robust two-step	Windmeijer-corrected two-step
Instrument count < groups	Yes	Yes
Estimator note	Arellano–Bond in differences	Blundell–Bond in system

Notes: Robust standard errors are in parentheses. ***, **, * denote significance at 1%, 5%, 10%. Negative coefficients imply lower CO_2 per capita (greater pollution reduction). AR(1) is expected; the insignificance of AR(2) supports the moment validity. Hansen and Diff-in-Hansen's disease support the instrument set.

Table 11
PQR-MM coefficient estimates (robust SE in parentheses)

Variable	τ=0.10	τ=0.25	τ=0.50	τ=0.75	τ=0.90
DGS	−0.018* (0.010)	−0.026** (0.011)	−0.033*** (0.012)	−0.041*** (0.014)	−0.039** (0.019)
REA	−0.041*** (0.012)	−0.056*** (0.014)	−0.071*** (0.016)	−0.083*** (0.018)	−0.079*** (0.022)
TI	−0.012 (0.009)	−0.018* (0.010)	−0.024** (0.011)	−0.029** (0.012)	−0.031** (0.014)
DGS×REA	−0.005 (0.003)	−0.007* (0.004)	−0.011** (0.005)	−0.014** (0.006)	−0.015** (0.007)
DGS×TI	−0.003 (0.003)	−0.006* (0.003)	−0.008* (0.004)	−0.010** (0.005)	−0.011* (0.006)
HCD	−0.022** (0.010)	−0.031*** (0.011)	−0.039*** (0.012)	−0.044*** (0.013)	−0.040** (0.017)
ET	−0.010 (0.008)	−0.015* (0.009)	−0.021** (0.010)	−0.024** (0.011)	−0.023* (0.012)
NRR	0.009 (0.007)	0.012* (0.007)	0.016** (0.008)	0.019** (0.009)	0.021** (0.010)
Constant	0.181 (0.121)	0.233* (0.125)	0.302** (0.136)	0.347** (0.152)	0.361** (0.171)
KP ark F (min across endow)	12.4	15.7	18.9	16.2	11.6
AR p-value (weak-IV robust)	0.036	0.012	0.004	0.01	0.041
CLR p-value	0.044	0.015	0.006	0.013	0.049
Over-ID J p-value	0.318	0.411	0.458	0.433	0.367
Quantile Exogeneity Score Test (H0: exon of all endog) p	0.029	0.017	0.008	0.014	0.037

Note: Significance: *** 1%, ** 5%, * 10%

adoption of renewable energy, and technological innovation, together with supportive human capital and fiscal policies, collectively stimulate a decrease in emissions, thereby multiplying their effects. Rigorous checks can strongly support these results, and the empirical findings are credible in relation to policy recommendations for the digital transition to an environmental policy.

4.5. *Endogeneity assessment using dynamic GMM*

The dynamic GMM evaluation demonstrates that this model is robust and that the findings are robust. The results are presented in Table 10. Both the Difference GMM and System GMM exhibit persistence in emissions, particularly with high lagged variables, indicating that the historical level of pollution has a profound influence on current emission levels. This enhances the dynamic approach and shows path dependency in environmental performance. The coefficients of digital government services (DGS), renewable energy adoption (REA), and technological innovation (TI) are negative and substantial in both estimators, proving their contribution to reducing CO_2 levels. The interaction terms indicate that DGS is more operative with renewable energy and innovation, and digital governance and technological advances collaborate to curb pollution. This is also true for human capital development (HCD) and environmental taxation (ET), which, although expected to have positive effects on environmental outcomes, are generally expected to have negative effects. In contrast, the measures of natural resource rents (NRR) are positive and significant, indicating that extractive rent dependency contributes to inflated emissions. Diagnostic tests confirmed the validity of the model. There is AR(1), as anticipated, but AR(2) is small, and therefore eliminates the second-order serial correlation. The Hansen and Sargant tests are not rejected for instrument validity, and the Diff-in-Hansen statistics in the system estimator indicate that the additional level moments are correct. The number of instruments was lower than the number of groups, which helps alleviate fear regarding the proliferation of instruments. The Wald test rejects the null hypothesis of no effect, which supports the explanatory power of the model.

Alternative instrument specifications and lag structures in the dynamic GMM were used to perform a series of sensitivity tests to further evaluate the robustness of the empirical results. In particular, the baseline measurement with the L2-L3 lag instruments was re-estimated with other lag depths (L2-L4 and L3-L4) and different designs of the instrument matrix (collapsed and noncollapsed). The qualitative results did not vary with different alternate settings. The expected signs, levels of significance, and economic magnitudes of the coefficients of DGOV, TI, REC, and the interaction terms (DGOV × TI and DGOV × REC) remained unchanged. In addition, the Hansen J-statistics and Sargant tests, along with the difference-in-Hansen diagnostics, always confirmed the instruments' validity, and the AR(2) tests still indicated that there was no second-order serial correlation. There were fewer instruments than cross-sectional units, which reduced concerns regarding the excessive number of instruments and overfitting. The results indicate that the estimated relationships are robust to the choice of instruments and lags. Thus, the pollution-reducing impacts of digital governance, technological innovation, and renewable energy sources, along with their complementary interactions, can be considered highly robust and reliable for various dynamic panel specifications(Michailidis, Kantartzis, Arabatzis, & Zafeiriou, 2025).

4.6. *Endogeneity mapping assessment with PQR-MM*

The final assessment included an endogeneity test, the results of which were obtained using the method of moments (PQR-MM). The difference in the effect of the interventions on reducing pollution was evident, and the results were uneven. The effect of digital government services (DGS) is negative in the lower quantiles of countries with relatively low CO_2 emissions and is relatively small. Most regressors in these settings are not rejected in exogeneity tests, implying that in less polluted settings, DGS and such reforms are less susceptible to reverse causality or unobservable dynamics, and that efficiency gains are small. The coefficients of DGS, renewable energy adoption (REA), and technological innovation (TI) are significantly larger and negative in all cases as we proceed from the median to higher quantiles. This means that in volatile regimes with a high rate of emissions, greater dependence on digital governance, the deployment of renewable energy, and technological advances considerably enhances the results of pollutant reduction. More importantly, the interaction terms between DGS and REA as well as between DGS and TI are significantly different at the 50th quantile and beyond. These findings indicate that DGS can best be combined with the adoption of renewable sources or innovations to create a complementary mechanism. A high level of digital governance, by itself, minimises emissions; however, when combined with green energy and the adoption of technology, it offers an amplified advantage. Diagnostic tests validated the applicability of the instruments and model specifications. The Klei Bergen-Paap rank F-statistics take values above 10 in all quantiles, eliminating the issue of weak instruments. The conditional Likelihood Ratio and Anderson-Rubin tests were used to identify the situation in weak IV-robust settings. Hansen over-identification statistics do not fall below the traditional significance levels, which confirms the validity of the instruments. The score-type endogeneity tests indicate that DGS and the terms of interaction are endogenous at the median and larger quantiles. These findings support the assertion that the variables should be included in the PQR-MM framework.

5. Discussion

This study aimed to investigate whether digital governance contributes to CO_2 emission reduction in N-11 economies and whether the impact is dependent on the innovative energy and governance systems in which it is applied. The empirical analysis's answer to both questions is, unsurprisingly, yes, and conditional to a larger degree than unconditional. The results, based on the CS-ARDL, CCEMG, and AMG estimators for the long- and short-run structures and with robustness checks conducted using dynamic GMM, Driscoll–Kraay fixed effects, Lebel-IV, Post-LASSO 2SLS, and panel quantile regression, consistently support the following three findings: (1) DGS has a significant and negative impact on CO_2 emissions; (2) TI and REA have a significant and negative impact on CO_2 emissions; and (3) the CO_2 emission-reducing power of DGS is considerably higher when either TI or REA is high. The findings extend the current literature on digital sustainability and ecological modernisation, which has so far ignored the interdependencies between digital governance, innovation capacity, and energy transition and regarded them as stand-alone levers.

One diagnostic result must be addressed before proceeding with variable-level results. The lagged CO_2 coefficient in the GMM specifications (0.618 in Diff-GMM and 0.702 in Sys-GMM) was large and significant. This is not only a technical product of dynamic specifications. This indicates that the environmental results of these economies are highly path-dependent, meaning that the results of the day are significantly influenced by the energy infrastructure, industrial investments, and institutions of the previous day. The message is that the benefits of digital governance, renewable energy, and innovation will be incremental and will not be achieved through short-cycle policy programs. The precondition for the type of structural environmental enhancement that the long-run cointegration estimates describe is sustained commitment, as opposed to occasional reform.

Digital government services lower CO_2 emissions not only because of their conditioning impact but also through their direct action. In the long run, the CS-ARDL coefficient is −0.0669, while in the short run, it is −0.0268, CCEMG returns -0.0786, and AMG returns -0.0424, all of which are significant at conventional levels. It can be concluded that hypothesis H1a is accepted. This directionality aligns with the expectations of the theoretical framework: digital public administration helps reduce the information gap between regulatory bodies and regulated entities, reduces the administrative cost of environmental enforcement, and expands the scope and space of compliance monitoring, both geographically and timewise (Mu, Liang, & Yang, 2025; Xie *et al.,* 2023). The sooner and at a lower cost emissions violations are identified, the better the compliance and the lower the emissions.

We would expect this long-run effect to be larger than the short-run estimate and logically consistent. Digital governance reforms show their full environmental impact over time and through institutional channels: platform maturity, administrative capacity development, behaviour change by the regulated enterprises and increasing maturity of the data infrastructure and its capacity to support a proactive environmental management approach. The pollution-abating role of digital government, based on data from 159 countries, is found by Zeng, Zhang, and Li (2025) to work through improvements in government efficiency, regulatory quality, and business environment – all accumulation processes. A study of provincial-level China by Wu and Zhang (2023) shows that citizen participation can reinforce the impact of e-government adoption on environmental outcomes, as captured in the institutional quality mechanisms of the current study's theory.

It is important to keep in mind that there is also a short-run effect. Economies in the N-11 category have rapidly expanded digitalisation investment since the mid-2000s, and the negative coefficient for the near term indicates that even initial digitalisation investment (before final institutional consolidation) can be identified as having a measurable effect on emissions reductions, likely due to the direct displacement of processes that were previously paper-intensive and the initial deployment of environmental monitoring platforms (Ma & Feng-lan, 2022; Chung, Choi, & Cho, 2022). The panel quantile regression results confirm this effect, which increases along the emission distribution (from −0.018 at the 10th quantile to −0.041 at the 75th quantile). Digital governance achieves its highest emissions savings where most are needed, and this has a direct impact on the priority of investing in digital governance in more emission-intensive N-11 countries in the future.

Technological innovation leads to a decrease in CO_2 emissions for all estimators, but with different magnitudes: −0.0944 (CS-ARDL long-run), −0.0824 (CCEMG), and weaker, but significant at 10%: −0.0174 (AMG). This supports Hypothesis H2a. This is what the literature refers to as the clean technology effect: innovation reduces the resource intensity of production and thus the carbon intensity to some extent, and consequently, the growth of carbon emissions is not tied to the growth of output (Han, Peng, Guo, Aslam, & Xu, 2025; Li, Elhaida, & Doytch, 2021). Han et al. (2025) found a negative relationship between technical progress and CO_2 concentration, specifically for the G-20 economies, where technical progress is achieved in the presence of policy frameworks and R&D investment—a situation that has been increasingly coming closer to the innovation environment of N-11, although in an uneven manner.

The smaller magnitude of the AMG coefficient is probably a true indication of heterogeneity and not estimator noise. Countries with weak absorptive capacity or less-developed domestic innovation systems reap lower environmental benefits from observed R&D and patenting, which is a limitation for some N-11 countries (Islam, Khan, Khan, Tabassum, & Hashim, 2021). Another risk of rebound is that innovations can lead to productivity gains that increase the overall demand for energy, partially offsetting the gains in clean technology, at least in economies where energy prices continue to subside and regulatory pressure is limited (Sinha, Shahbaz, & Balasore-Lorente, 2017). The present results indicate that the net effect is negative (i.e. innovation leads to emission reductions in the N-11 panel), but that this is not the same across countries and that this is not robust to scale effects. The quantile regression also shows that the environmental return of innovation is greatest at higher levels of emissions (−0.031 at $\tau = 0.90$ versus an insignificant −0.012 at $\tau = 0.10$), indicating that innovation's impact on the environment is most important in higher-pollution sectors, where there are more opportunities for abatement.

The most consistent and largest emission reductions are those of renewable energy adoption: CCEMG returns are −0.0695 long run, AMG −0.0484, and the quantile estimates range between −0.041 at $\tau = 0.10$ and −0.083 at $\tau = 0.75$. Thus, hypothesis H3a is supported. One of these estimates is noteworthy here: the absolute value of the short-run estimate (CS-ARDL, −0.0431) exceeds that of the long-run estimate (−0.0291). This is not simply a statistical artefact but rather an interpretable finding. Renewable energy substitution has a front-loading effect: carbon abatement is achieved when fossil generation capacity is substituted, and when deployment starts, it occurs quickly. However, in the longer term, emissions pressures from increased economic activity as a result of cheap renewable energy somewhat offset the emission reductions from primary actions (Adanma & Ogunbiyi, 2024). The net long-run impact is still negative; however, the size of the impact is more complex and requires a more dynamic adjustment process than the short-run impact alone suggests.

Looking at the N-11 economies individually, Wang et al. (2022) found that renewable energy use lowers the ecological footprint when democratic institutions are in place and of good quality, which the co-significance of HCD and ET in the specifications of the current study empirically supports. As an illustration of the integrated mechanism, the Copenhagen case study referred to by Christensen (2024) is helpful, albeit stylised. A high proportion of renewables, a digital platform for grid management, and a legislative framework with a clear focus on emission reduction all contributed to achieving significant urban emission reduction. This integration is exactly what the triadic model captures: the impact of renewables on the environment is not self-contained but occurs through the mediation and amplification of the institutional capacity that digital governance offers in the context of national governance, in this case, N-11. In the extended model, the interaction term DGOV×TI was negative and significant for all estimators, with estimators ranging from −0.0282 (AMG) to −0.0638 (CCEMG). The unambiguous results of the marginal effect analysis are −0.0728 for low TI, −0.1039 for mean TI, and −0.1350 for high-TI. Thus, H2a (in a moderating form) is supported. Digital governance and innovation capacity are not mutually exclusive but are complementary.

The mechanism is simple and is as follows. Digital governance establishes a data infrastructure, compliance monitoring systems, and data channels that enable innovation systems to function effectively on a large scale (Nambisan et al., 2017; Wang et al., 2023). Technologies that enable the monitoring of emissions, digital reporting by industry, satellite monitoring of the environment, and automated compliance scoring are all innovations that need to be developed and deployed, as well as a digital governance backbone to make them part of the system. If innovation capacity is low, governance platforms do not have the technological input to achieve environmental potential; if it is high, governance infrastructure directs clean technology outcomes towards environmental targets more precisely (Fazal & Azam, 2023; Ramzan, Razi, Quddus, & Adebayo, 2022). What does this interaction have with N-11? An equivalent amount of digital governance investment in a low-innovation economy (Bangladesh and Nigeria) is associated with systematically lower environmental returns than an equivalent investment in more innovation-rich countries (South Korea and Turkey). This implies that a differentiated policy design (as opposed to a uniform design) is required for each group.

The most significant finding of this study was the interaction between the DGOV and REC. Both CS-ARDL estimates of the long-run coefficient, namely −0.0674 and CCEMG −0.0729, are greater than the DGOV×TI coefficients in all specifications. The most obvious indication of triadic logic is the marginal effect gradient, which equals −0.0365 for low renewable energy consumption, −0.1039 for mean consumption, and −0.1713 for high consumption. This is far from a moderating effect in the low-to-high renewable penetration context; it is a qualitative change in the environmental return on digital governance investment depending on the meaning of the energy system transition to renewables.

Several complementary mechanisms operate in concert to fuel the mechanism. Digital governance platforms simplify the administrative procedures required for renewable energy deployment, such as online licencing and permitting, grid integration coordination, renewable energy certificate management, and transparent consumption reporting (Zhang & Ullah, 2023). The digitisation of energy systems is at the heart of smart grid technologies, which enable the real-time control of variable energy resources, such as solar and wind power, to reduce energy losses and increase the total contribution of renewables to the energy mix (Stankovic & Neftenov, 2022; International Renewable Energy Agency, 2019). This is because energy system decarbonisation will also lead to a decrease in the carbon footprint of the digital economy, creating a positive feedback loop between the two transitions (Shahbaz, Dong, Dong, & Taghizadeh-Heary, 2022). The importance of the DGOV×REC interaction compared to the DGOV×TI interaction indicates that the renewable energy channel is the main channel for decarbonisation through digital governance in the N-11 sample, with direct implications for the prioritisation of decarbonisation policy.

There is a consistently positive and significant link between natural resource rents and CO_2 emissions for all estimators and specifications. The CS-ARDL long-run coefficient was 0.0341, the short-run coefficient was 0.0152, and the CCEMG and AMG coefficients were 0.0264 and 0.0352, respectively. For the N-11 panel, the resource curse hypothesis is confirmed. Some members of the group are strongly dependent on hydrocarbon rents, such as Nigeria, Iran, and Mexico, and the results show that this dependence entails environmental costs. There is also a carbon intensity of hydrocarbon extraction, and fiscal policies enable a delay in energy transition when hydrocarbon rents are high, as well as institutional distortions from resource dependence (Mesagan &

Vo, 2023; Mensah, Ofori-Boateng, Asante, Acheampong, & Maruha, 2023). Most importantly, the positive NRR coefficient causes structural counterpressure to the synergies identified between digital governance and renewables or innovation, which have an impact on emissions. Therefore, it is necessary to make the governance of the resource sector a specific part of the digital and green transition policies to achieve the environmental potential of the aggregated policies.

As expected, environmental taxation has a negative and significant impact on all coefficients, ranging from −0.0090 (AMG, 10% level) to −0.0398 (the long-run coefficient in the CS-ARDL model). The magnitude of the estimates decreases from long-run to short-term estimates, which aligns with the literature on environmental economics and the findings for the N-11 context (Boateng, Asafo-Adjei, Agyei, & Hammah, 2024), suggesting that the behavioural adjustment of firms and households in response to persistent carbon price signals varies, with a longer time horizon providing a stronger signal. Human capital development is negative and highly significant under all estimators, including the largest AMG estimate in absolute terms (−0.0644). The preferences of educated population groups for the environment, compliance with regulations, and their ability to absorb clean technologies are high (Mu *et al.* 2025; Sun, Razzaq, Sun, & Irfan 2023). The relative uniformity of the HCD results between the widely divergent cross-sectional dependence/slope heterogeneity estimators further bolsters the argument that human capital is not just a control variable on the periphery, but also an environmental policy instrument itself in the N-11 context.

These findings are consistent with the three theoretical pillars of the conceptual framework and are productive. Ecological Modernisation Theory is directly supported because digital governance is an institutional modernisation process based on the perception that digitalisation is likely to lead to a decoupling of economic activity from environmental degradation, and that the decoupling is indeed enhanced—as the theory would predict—by co-evolutionary gains in technological capability and energy system composition (George et al., 2020; Shen *et al.,* 2022). The EKC hypothesis provides partial empirical evidence. The quantile evidence, which suggests a greater impact of DGS at higher levels of emissions, is consistent with the EKC reasoning that higher levels of income and emissions are where the greatest environmental gains are to be achieved through institutional governance reform (Zhong, 2022; Dinda, 2004).

The findings of the interaction support the dimensions of the Technology Acceptance Model in the framework. TAM suggests that usefulness and ease of use have a governing influence on technology adoption, and moderation evidence indicates that digital governance positively influences the perceived accessibility of RE and clean tech adoption, consequently speeding up the diffusion process in the context of N-11 (Fred, 1989; Wa & Zhang, 2023). This adds to the literature by offering macro-level empirical evidence of a mechanism that has been theorised at the individual or firm level. More generally, this study's main theoretical contribution is the empirical validation of a triadic synergy model of digital governance, innovation capacity, and renewable energy transition, suggesting that these policies can be regarded not as separate policy instruments but as a system that reinforces each other. Previous studies on N-11 effects on the environment have focused on one factor (Sinha *et al.*, 2017; Wang, You *et al.,* 2022). The evidence presented here on the interaction shows that the combined effect on the environment is significantly greater than the sum of the individual effects, which provides a theoretical fine-tuning and practical policy argument for a coordinated (rather than sequential) approach to reform.

6. Policy Recommendations

The empirical results present six interconnected policy imperatives based on specific findings tailored to the institutional realities of N-11. These recommendations are based on one overall conclusion: digital governance, technological innovation, and renewable energy transition are not three levers to be turned one after the other. The evidence in the interaction clearly indicates that they are dependent on each other and that emission reduction in N-11 is only feasible to the extent to which policies address these three dimensions as a system and not as competing demands on limited budgets.

This is the direct negative impact of DGS on CO_2 emissions, which is pronounced in both the short and long terms and is growing along with the distribution of CO_2 emissions. Governments should establish fully integrated national digital environmental management systems that include a single interoperable architecture, real-time emission monitoring, regulatory compliance reports, environmental permits, and interministerial data sharing. The use of IoT sensor networks for industrial emissions monitoring, satellite monitoring with automated enforcement triggers, and blockchain-based environmental reporting can help reduce the information gaps currently hindering the effectiveness of environmental regulations in some N-11 countries (Chohan & Hu, 2020; Chung *et al.,* 2022).

The quantile evidence suggests that the increase in environmental returns from investing in digital governance is highest for the higher-emission N-11 countries, including Indonesia, Nigeria, Iran, and Mexico. The CS-ARDL estimates in this study show that even if only a portion of the fleet is deployed, as in the power, transportation, and heavy industry sectors, short-term emission reductions can be achieved. Technical cooperation should be sought through international institutional collaborations, such as the UN E-Government program and the IEA digital energy program, for both the design of the platform and the standardisation of the data, and for the creation of the cross-border monitoring protocol.

The strongest policy signal in the study is the DGOV×REC interaction evidence, which shows that the impact of digital governance increases from −0.0365 to −0.1713 in the low and high renewable penetration contexts, respectively. This shows that renewable energy capacity and digital governance infrastructure are complementary investments; that is, the returns of the two investments are compounded when they are both used. Governments should build the need for digital infrastructure in their renewable energy expansion schemes, such as smart grid deployment, AI-based forecasting of renewable energy demand, digital metering, and cloud-based renewable energy certificate markets.

Prioritisation should be given to online permitting systems for renewable energy projects, as the front-loaded short-run renewable coefficient demonstrates that permitting process improvements that enable renewable energy project adoption also leads to near-term emission reductions (International Renewable Energy Agency, 2019; Zhang & Ullah, 2023). The financing of this investment may be partly funded by wealth funds based on hydrocarbons that directly tackle the resource curse effect identified by the positive NRR coefficient for N-11 economies with high resource rents. This recommendation can be implemented by earmarking the share of resource rents for clean energy and digital governance transition investments.

The DGOVxTI × TI interaction shows that the effect of digital governance on the environment is even larger in the context of higher innovation capacity, with the marginal effect being approximately double at low and high levels of innovation capacity. This discovery gives rise to a particular requirement for innovation policy: R&D funding schemes must consider environmental performance aspects and should not be used as a general productivity tool. A percentage of the public investment in research should be spent on clean production technologies, digital solutions for environmental monitoring, energy storage, and smart applications for infrastructure. Fiscal measures such as green patents, faster depreciation of clean technology capital, and public procurement pledges for domestically developed environmental technologies can encourage private innovation along these pathways that add up to digital governance benefits (Johnstone, Haščič, & Popp 2010; Han *et al.* 2025).

International technology transfer agreements under multilateral negotiations (the UNFCCC technology mechanism and bilateral clean technology cooperation programs) offer an alternative way to access innovation for lower-innovation N-11 members in which the attenuated AMG coefficient indicates absorptive capacity constraints in the domestic development of clean technologies. Green innovation hubs that are co-located with existing digital economy clusters, facilitated by university-industry-government R&D consortia with a clear green mandate, can lead to faster commercialisation of green technologies by both high- and low-capacity group members by facilitating knowledge spillovers and sharing of infrastructure.

The uniform and significant environmental tax coefficients support the conclusion that fiscal carbon pricing is an effective abatement instrument, while the relatively small tax coefficients compared to the DGS and REA effects indicate that the current level of carbon taxes in most N-11 economies is below the optimal level of abatement tax. Governments should have realistic, well-publicised plans for escalating environmental taxes over the long term to allow enough time for regulated organisations to make capital and energy procurement adjustments, as well as provide a long-term behavioural response to environmental taxes, as suggested by the long-run coefficient compared to short-term estimates (Boateng *et al.,* 2024). The predictability of carbon prices helps decrease uncertainty and prevents regulatory arbitrage, thus promoting investment in clean technology.

The effectiveness of environmental taxation depends on its enforcement capacity, which is directly provided by digital governance. The channels through which digital governance can reduce emissions (Mu *et al.,* 2025; Xie *et al.,* 2023) are the same as those through which compliance with carbon pricing can be monitored and enforced. As a result, environmental tax revenues should be earmarked for digital environmental governance infrastructure and research and development into clean technology, so that there is a fiscal feedback effect, and carbon pricing revenues are used for the institutional capacity to implement carbon pricing. This revenue recycling model is especially suitable for N-11 economies that face fiscal constraints in making standalone public investments in digital reform.

The consistently negative HCD coefficients for all estimators further support the notion that human capital is a first-order environmental policy tool rather than a second-order tool for emission analysis. This workforce development policy reconfiguration is followed by the following: digital literacy and environmental competency must be regarded as a skill package that must be acquired to participate in digitally led, low-carbon economies. Technical and vocational curricula should include environmental data analytics, renewable energy system operation and maintenance, electronic compliance reporting, and sustainable production management. These are not specialised add-on programs to the existing ones, but essential skills of the economies the N-11 is on the way to becoming.

Public administration officials, through environmental regulators or energy policy agencies, can be systematically upskilled in the use of digital governance tools, ranging from emission databases to interfaces for monitoring from space to AI support for enforcement prioritisation. The theoretical relationship between human capital and digital governance embedded in a system of complementarities suggests that investments in one country without another result in systematically lower returns in the environment. Additionally, the N-11 group for South-South cooperation has the untapped capacity to provide structured technical assistance from higher-capacity members (South Korea and Turkey) to other members (Bangladesh, Nigeria, and Pakistan) to lower the cost and time needed for institutional capacity building across the group.

The path dependency of emissions (also seen in the large coefficients of lagged dependent variables in the GMM specification) suggests that while individual country actions are essential, there are structural constraints to overcome the inertia of fossil energy systems, dependence on the resource sector, and technology diffusion lags. Multilateral coordination of N-11 economies can create opportunities for economies of scale in the deployment of green technology and sharing benefits in the development of digital governance platforms in terms of sharing infrastructure and enhancing the negotiating capacity of the group in international discussions on technology transfer and climate finance.

A green digital alliance with a voluntary cooperation mechanism between N-11 governments could lead to the mutual recognition of renewable energy certification systems, interoperability of national digital environmental monitoring systems, joint procurement of satellite-based technologies for environmental monitoring and surveillance, and coordinated clean innovation investment. The empirical evidence for such coordination is clear, as digital governance and renewable energy are complements and the environmental gains of their combined use are much larger than the sum of national programs. Investment decisions can be coordinated across groups to achieve aggregate emission reductions beyond the sum of national programs. This is not just a matter of regional environmental governance but also one with global climate implications, as this set of economies will make the largest contribution to global emission pathways in the coming decades.

7. Conclusion and limitations

This study explored the impact of digital government services on pollution reduction in N-11 developing economies, with a special interest in the moderating effects of technological innovation and renewable energy utilisation. This study created a triadic model connecting digital governance, innovation capability, renewable energy transition, and environmental performance based on annual panel data from Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, South Korea, Turkey, and Vietnam (2003–2022). An array of advanced panel methods, such as CS-ARDL, CCEMG, AMG, dynamic GMM, and panel quantile regression, were used for the empirical analysis. These techniques enable this study to account for properties that may arise, such as cross-sectional dependence, slope heterogeneity, long-term cointegration, dynamic persistence, and potential endogeneity. The results offer strong evidence that the use of digital government services has a negative impact on CO_2 emissions in the short and long terms. This discovery shows that e-government can play a role in environmental improvement, both in terms of improving administrative efficiency, regulatory monitoring, reducing information gaps, and enhancing transparency in public governance. There were also significant negative impacts on emissions from technological innovation and renewable energy use, further underlining the importance of cleaner technologies and transitioning to renewable energy for pollution abatement. Most importantly, the interaction terms confirmed the main hypothesis of the study. The negative and significant coefficient of the interaction of DGOV × TI indicates that the effect of DGOV is stronger when countries have higher technological capacity, whereas the negative and significant coefficient of DGOV × REC indicates that the effect of DGOV is stronger when countries have more renewable energy use. Digital governance also has larger emission reduction effects as innovation levels increase under greater shares of renewable energy. These findings fit in with the literature on ecological modernisation, digital governance, renewable energy, and environmental sustainability. Previous research indicates that the digital transformation of the government makes it more efficient and better able to monitor the environment, and that renewable energy decreases fossil fuel reliance and emissions. Similarly, technological innovation enhances production efficiency and accelerates the incorporation of cleaner technologies. Many previous studies have investigated each of these factors. This study adds to the evidence that digital governance is not a standalone environmental policy instrument. However, its impact cannot be realised without supportive technological and energy systems. The results further support the idea that digital transformation, innovation capacity, and renewable energy transition go hand-in-hand and, therefore, are best studied and implemented as part of sustainable development. This study makes three main contributions to the literature. First, it offers fresh data from the N-11 economies, which comprise a range of developing countries with high growth in energy demand, rapid urbanisation, growing digital infrastructure, and growing environmental pressures. Second, it contributes to the literature by (1) testing the moderating role of technological innovation in the digital governance and pollution nexus and (2) testing the moderating role of renewable energy adoption in the digital governance and pollution nexus. Third, it enhances empirical credibility by using several estimators and robustness checks. These results indicate that governments should consider integrating digital transformation strategies, green technology policies, and renewable energy plans at the policy level. An e-government platform should enable real-time monitoring of emissions, permitting renewable energy, smart grid coordination, and transparency in environmental compliance. Meanwhile, more investment is needed at the government level in skills, clean technology research, and environmental tax measures for a better digital green transition. Limitations of the study: This study is based on macro-level data and does not necessarily reflect differentiation at the sector, firm, or regional policy levels. Future research studies should be implemented with industry-level or firm-level data, analyse the carbon cost of digital infrastructure, and assess the effectiveness of digital environmental governance according to institutions.

The macro-level approach to the research undertaken provides general information about the research; however, it does not reveal differences across sectors or regions. Future research should use micro-level (or industry-centric) analysis to identify situational variations in the effects of digital governance on the environment. These two measures of innovation, based on patent activity and R&D intensity, may fail to reflect the qualitative measures of technological development. Indirect signals such as green patent citations or innovation diffusion rates can also be featured in future research. Investigating the impact of digital infrastructure on the environment, data energy usage, and digital waste provides valuable insights into the emerging phenomenon of digital sustainability. The identified gaps will enable a deeper understanding of the relationship between digital transformation and environmental governance and provide a sustainability model for the digital era. Furthermore, CO_2 per capita is often used but is not comprehensive enough to encompass all aspects of pollution. It does not contain any local air pollutants, such as PM2.5, SO2, or NOx. It also does not consider land, waste, water pollution, or material footprint. In future research, the digital governance pathway could be tested for consistency with respect to other environmental indicators, including PM2.5, ecological footprint, carbon footprint, and load capacity factor.

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Conflicts of interest/Competing interests

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Availability of data and materials

All data used in this study are publicly available from recognised sources, including the World Bank's World Development Indicators (WDI), the International Energy Agency (IEA), UNESCO, WIPO, and the United Nations E-Government Survey.

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