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Can Good Governance Make Digitalization Environmentally Sustainable? Evidence from Pakistan

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ABSTRACT

This study investigates the asymmetric impact of information and communication technologies (ICT) on ecological footprint in Pakistan, incorporating governance as a moderating factor. Using a nonlinear ARDL framework, the analysis distinguishes between positive and negative shocks in fixed broadband subscriptions and internet usage. The results confirm long-run cointegration and reveal that digital expansion increases ecological pressure, largely due to fossil fuel–based energy dependence. However, governance quality significantly mitigates these adverse effects by moderating the ICT–environment nexus. The findings highlight the importance of institutional strength and energy transition policies in ensuring that digital transformation contributes to environmental sustainability in developing economies.

DETAILS

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1. Introduction

Ecological footprint in the world keeps surpassing the regeneration capacity of the Earth; there are structural pressures due to production, consumption, and demographic change. The Global Footprint Network states that nowadays, the equivalent of approximately 1.7 Earths is consumed to satisfy the annual demand for resources, and high-income economies occupy a disproportionate portion of the overshoot (Lin et al., 2018). The leading cause is carbon emissions, which take up about 60 percent of the overall environmental footprint and are directly associated with reliance on fossil fuels and fuel-demanding supply chains (World Wildlife Fund, 2022). The change in land-use and the loss of biodiversity only exacerbate the issue; according to the Living Planet Index, by 1970, on average, 69% of the wildlife populations discussed in the index have been reduced (population) as a result of ecosystem degradation as opposed to climate change alone (World Wildlife Fund, 2022). With the rapid urbanization and material extraction, water stress and soil depletion, the global material consumption is more than three times higher than the efficiency gain, and sustainability transitions are hindered (Devezas et al., 2017).

With the national contexts of increasing population, reliance on energy, and development based on resource consumption, Pakistan is experiencing pressure for an increase in its ecological footprint. Demand in the country is mainly characterized by carbon and the cropland areas because the country heavily relies on fossil fuels and experiences low agricultural productivity. The data from the World Bank suggests that the energy mix in Pakistan is still more than 60% fossil-based, which adds to the increase in emissions in the country, whereas per-capita emissions are relatively insignificant (Climate Transparency, 2020). Meanwhile, the fast urbanization process and the unproductive use of water contribute to the tensions of land and water. Pakistan is one of the most water-stressed nations in the world, and its water availability per capita is below 900 cubic meters, as opposed to 5000 plus in the 1950s (Zahoor & Riaz, 2025). Deforestation also negatively affects bio capacity; the forest area is around 5 percent of the total land area, which reduces carbon sequestration and ecosystem ability (Imran, 2025). These structural imbalances constrain sustainable growth and amplify vulnerability to climate-related shocks.

The current empirical evidence has centered on policy, finance, and circularity as practical interventions towards reducing ecological footprints. EU economies are characterized by higher rates of recycling, so as to invest in a circular economy better placed to reduce footprint aspects, and higher rates of municipal waste creation and strain on bio capacity (Chen & Pao, 2024). According to cross-country studies, stringency in environmental policy lowers ecological footprint, and the effect of this is realized by adopting renewable energy and being able to innovate (Sohag et al., 2024). Some supplementary evidence also shows a higher reduction at higher quantiles of degradation, which means that tight regulation works best when the overshoot has already been extreme (Nabi et al., 2025). Time-series and panel analysis in the finance channel demonstrate that, with the support of capital, green power, and efficiency, green finance and green growth are linked to the decrease of ecological footprints (Jóźwik et al., 2025; Zhang & Chen, 2023). Findings stay consistent on policy combinations: Substituting single-instrument policies with policy blends, forged on fiscal stimuli, clean-energy investment, and the circular design, become superior.

This research has various contributions to the literature. To begin with, it enhances the study of the ICT environment nexus because it uses a nonlinear ARDL model where the asymmetric impacts of growing digital expansion and shrinking are analyzed. Second, it brings in governance as a moderating process, which provides institutional learning on the evidence of how digitalization leads to environmental results. Third, it centers on Pakistan, which is more specific since it offers a context-relevant piece of evidence of a developing, energy-constrained economy whose digital growth is speeding up. Fourth, dual ICT proxies are present, which increases the measurement strength. The study, overall, makes a contribution by closing digitalization, institutional quality, and ecological sustainability in one empirical framework that applies in the emerging economies.

2. Literature Review

Information technology ICT empirical evidence has been associated with ecological footprint by competing efficiency and scale processes. Referring to Saudi Arabia, (Kahouli et al., 2022) state that ICT, along with green energy and productivity increase, is considered to have a minimized ecological footprint, which is in line with technique effects that lessen resource intensity. Cross-country studies point to heterogeneity: (Kazemzadeh et al., 2023) observe that the impact of ICT is better across panel quantiles of ecological footprint, indicating that the positive effect of ICT on ecological savings is more likely within less ecologically supportive regulatory capacity and energy infrastructure. Recent cross-country studies also report heterogeneous marginal impacts of individual ICT indicators, and composite digitalization measures are generally associated with a higher quality of the environment, including reduced ecological footprint (Charfeddine et al., 2024). The exchanges around the mechanisms note that ICT can facilitate dematerialization and smarter logistics, but produces a rebound of increased consumption and faster replacement of equipment (Hilty & Aebischer, 2015; Werner, 2014). Such rebounds are important as the ICT sector has a nontrivial energy of the lifecycle itself and device, networks, and data center burdens (Belkhir & Elmeligi, 2018; Malmodin & Lundén, 2018). Privately, numerically, most studies generalize STIRPAT/EKC specifications with nonlinearities, interactions, and endogeneity conditions, indicating that the benefits of ICT are conditional on the renewable penetration and income levels and not consistent across both time and countries.

Governance quality is becoming a conditioning variable in empirical research as it clarifies whether ICT expansion generates ecological or environmental pressure. Research based on the STIRPAT and EKC paradigms revealed that ICT has mixed implications on the ecological footprint, although the implications are systematically negative in those nations with a stronger institutional capacity. (Salahuddin et al., 2018) illustrate that environmental degradation can only be minimized by the presence of ICT in cases where the quality of regulation and effectiveness of governments are sufficiently high, with institutions supporting energy-efficiency regulations, digital monitoring, and enforcement. On the same note, (Khan & Hou, 2020) discovered that governance indicators, especially the rule of law and control of corruption, moderate the ICT environment nexus by mitigating the rebound effects of increased digital consumption. Evidence of cross-country panels obtained by (Charfeddine & Kahia, 2019) also testifies that the ICT-intensive decrease of ecological footprint can be even higher in economies with open institutions and effective environmental policies, since the digital technologies have higher chances of being used in smart grids, e-government, and in resource-saving production. Conversely, poor governance situations enable ICT diffusion to create scale effects through raising energy demands and electronic waste that counteract efficiency benefits. This conditional view is consistent with the institutional economic suggestion of the importance of governance quality that can realize the digitalization, either favoring the ecological sustainability or propagating unsustainable consumption patterns.

3. Data and Methodology

3.1. Data

To investigate the existence of any influence of ICT on the ecological footprint of Pakistan and whether governance can also serve as the moderator between this nexus, this research gathered information through multiple sources from 2005 to 2024. The annual data, however, is transformed into quarterly data to analyze it. The empirical variables, measures, and sources of data applied to test the relationship between information and communication technologies, governance, and ecological footprint are summarized in Table 1. Ecological footprint per capita is the dependent variable, which is a measure of the global hectares of environmental pressure. Digital infrastructure and access technologies are proxyed by the penetration of ICT, i.e., the fixed broadband subscriptions and internet use. The quality of governance has been used as a moderating variable, and it happens to be regulatory quality based on the Worldwide Governance Indicators. Control variables explain some important structural and macroeconomic determinants, such as urbanization, income level, energy use, and remittance inflows. Each variable is derived from internationally accepted databases, thus making it cross-country comparable and reliable in terms of data.

Table 1. Variable Description and Sources

Variable	Measurement	Source
Dependent variable		
Ecological Footprint (EFP)	Ecological Footprint per capita, measured in global hectares (gha/person)	Global Footprint Network (GFN)
Independent variables		
Fixed broadband subscriptions (FBB)	Fixed broadband subscriptions per 100 inhabitants	World Development Indicators (WDI)
Internet users (INT)	Individuals using the Internet (% of population)	World Development Indicators (WDI)
Moderating Variable		
Governance quality (GOV)	Regulatory Quality index (ranges approximately from −2.5 to +2.5)	Worldwide Governance Indicators (WGI)
Control Variables		
Urbanization (URB)	Urban population (% of total population)	World Development Indicators (WDI)
Economic growth (GDP)	GDP per capita (constant 2015 US$)	World Development Indicators (WDI)
Energy consumption (EN)	Energy use per capita (kg of oil equivalent per capita)	World Development Indicators (WDI)
Remittances (REM)	Personal remittances received (% of GDP)	World Development Indicators (WDI)

3.2. Model

In order to check the impact of ICT on ecological footprint, below mentioned equation is used.

$$EFt = \beta 0 + \beta 1 ICTt + \beta 4 URBt + \beta 5 GDPt + \beta 6 ENt + \beta 7 REMt \quad \text{eq (1)}$$

To check the moderating role of governance between ICT and ecological footprint, Eq-2 is used

$$EFt = \beta 0 + \beta 1 ICTt + \beta 2 GOVt + \beta 3 (ICT \times GOV)t + \beta 4 URBt + \beta 5 GDPt + \beta 6 ENt + \beta 7 REMt \quad \text{eq (2)}$$

Where, EF_t is ecological footprint, ICT_t is information and communication technologies measured by fixed broadband subscriptions and internet users, GOV_t is governance measured by regulatory quality, URB_t is urbanization, GDP_t is economic growth, EN_t energy consumption, REM_t remittance.

3.3. Non-Linear ARDL

Non-linear ARDL (NARDL) is an extension of the Pesaran-Shin-Smith ARDL model, where asymmetric adjustments are permitted to an increase or a decrease in one of the explanatory variables. It breaks down all regressors into positive and negative partial-sum processes and estimates both long-run and short-run separately within an error-correction model (Shin et al., 2014). The method is familiar with small samples, mixed integration of I(0)/I(1), but does not have series I(2), and it preserves the logic of bounds-tests of cointegration (Pesaran et al., 2001). Practically, ICT and governance can be modeled in such a way that the digital expansion and digital contraction may imply different outcomes on the ecological pressure, and the pace of reversion represents how fast the deviations of the equilibrium are rectified. Dynamic multiplier graphs follow the adjustment path in response to positive and negative shocks, allowing tests of long and short-run asymmetry to be conducted formally. Researchers frequently incorporate terms of interaction to determine whether the effect of institutional quality in reducing rebound effects and enhancing efficiency channels would strengthen with time.

4. Results

4.1. Descriptive Statistics

The results of descriptive statistics are provided in Table 2. The mean statistics show that there was a moderate variation of variables over the 80 observations. The value of the ecological footprint (EFP) is 8.208 global hectares per capita with a low dispersion (SD = 0.052), which indicates environmental pressure does not vary greatly. ICT indicators are more dispersed: the fixed broadband subscriptions (FBB) are more widely distributed (SD = 0.721) than internet users (INT) (SD = 0.214), a progressive digital growth. The quality of governance (GOV) has a negative mean (-0.685), which means that it has quite weak regulatory performance over the sample period. Urbanization and GDP exhibit gradual progressive growth, with the lack of dispersion between positive and negative values, which is a characteristic of slow structural change. The energy use is not too volatile, and remittances are moderately variable, which may affect domestic consumption and ecological demand.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
EFP	80	8.208	0.052	8.110	8.299
FBB	80	5.939	0.721	4.164	6.526
INT	80	1.070	0.214	0.802	1.437
Gov	80	−0.685	0.112	−0.901	−0.498
URB	80	1.557	0.019	1.530	1.593
GDP	80	11.476	0.092	11.324	11.614
EN	80	2.648	0.016	2.623	2.673
REM	80	0.754	0.150	0.470	0.973

Notes: EF_t is ecological footprint, FBB is fixed broadband subscriptions, INT is internet users, GOV_t is governance measured by regulatory quality, URB_t is urbanization, GDP_t is economic growth, EN_t energy consumption, REM_t remittance.

4.2. Unit root Test

The unit root results in Table 3 indicate that most variables are non-stationary at level but become stationary after first differencing, supporting an I(1) order of integration. Under the DF-GLS test, EFP, INT, GOV, GDP, EN, and REM fail to reject the unit root null at level but are significant at first difference. FBB and URB appear stationary at level under DF-GLS. The KSUR test, which accommodates nonlinear adjustment, largely confirms these findings: most variables are non-stationary in levels but strongly significant in differences. The mixture of I(0) and I(1) variables, with none integrated of order two, satisfies the key precondition for applying the ARDL and NARDL modelling framework.

Table 3. Unit root test

	DF-GLS				KSUR			
DF-GLS	Level		Diff		Level		Diff	
Variable	Stat		Stat		p-value		p-value	
EFP	−1.420	(IS)	−4.870	Sig	0.184	(IS)	0.000	Sig
FBB	−1.094	(Sig)	−5.120	Sig	0.267	(IS)	0.001	Sig
INT	−1.312	(IS)	−4.560	Sig	0.143	(IS)	0.002	Sig
Gov	−0.980	(IS)	−3.940	Sig	0.221	(Sig)	0.004	Sig
URB	−1.676	(Sig)	−4.210	Sig	0.091	(Sig)	0.000	Sig
GDP	−1.181	(IS)	−5.430	Sig	0.198	(IS)	0.000	Sig
EN	−1.360	(IS)	−4.890	Sig	0.176	(IS)	0.001	Sig
REM	−1.020	(IS)	−3.780	Sig	0.239	(IS)	0.006	Sig

"Note: GF-GLS does not assume stationary nonlinear, whereas the KSUR unit root test presented by Kapetanios & Shin (2008) considers stationary nonlinear. The null hypothesis assumes the presence of a unit root."

4.3. Co-integration Test

The ARDL bounds test results in Table 4 confirm the existence of a long-run equilibrium relationship among the variables. For Model 1, the computed F-statistic (6.214) exceeds the upper-bound critical value at the 1% level (4.680), leading to rejection of the null hypothesis of no co-integration. Similarly, Model 2 reports an F-statistic of 5.487, which also surpasses the 1% upper-bound threshold. Since both statistics are well above the upper bounds at conventional significance levels (1%, 5%, and 10%), the results provide strong evidence of long-run co-integration between ecological footprint, ICT indicators, governance, and control variables. These findings justify proceeding with long-run and short-run ARDL/NARDL estimations, including error-correction representations to capture adjustment dynamics toward equilibrium.

Table 4. ARDL bounds co-integration Test

ARDL bounds co-integration Test	F-stat	Result
Model 1	6.214	Co-integration
Model 2	5.487	Co-integration
Lower-bound critical value at 1%		3.410
Upper-bound critical value at 1%		4.680
Lower-bound critical value at 5%		2.620
Upper-bound critical value at 5%		3.790
Lower-bound critical value at 10%		2.960
Upper-bound critical value at 10%		3.350

4.4. Nonlinear ARDL Estimation

The nonlinear ARDL findings in Table 5 indicate the presence of an evident asymmetry in the long-term footprint of the ICT nexus and ecological footprint. In Model 1, positive shocks to fixed broadband (FBB^+) and internet use (INT^+) have a strong effect on the ecological footprint, as the former raises the state of the environment and the latter decreases it, and is not statistically significant, proving the asymmetrical environmental reaction to digital growth and decline to digital meets. Energy consumption has a robust impact on dream and nightmare regimes in both positive and negative directions, which consolidates its leading role in causing ecological pressure. In the long run, urbanization and economic growth are also beneficial, which is also in line with scale effects. In model 2, these relationships are moderated by governance. The negative sign of GOV, and the interaction effect between FBB and GOV, as well as INT and GOV, indicate that the better the quality of regulation, the lesser the negative effects of ICT expansion on the environment. What this means is that institutional quality attenuates rebound effects and contributes to digitalization in terms of efficiency gains. These results are in line with those that state that ICT brings about immediate ecological pressure due to increasing energy demands, but changes to a favorable environmental outcome with strong governance and cleaner energy systems (Hao et al., 2022; Zahid et al., 2025). Asymmetric pattern is also supportive of recent nonlinear results of the finding related to digitalization in the sense that the impacts of digitalization vary according to the positive and negative shocks, which is superior to the use of NARDL to specifications of linearity.

Table 5. Nonlinear ARDL estimation

Long-run	Model-1	Model-2
EF_{t-1}	0.298*	0.203*
FBB^{+}_{t-1}	0.882***	0.614**
FBB^{-}_{t-1}	−0.395**	−0.268*
INT^{+}_{t-1}	0.731***	0.492**
INT^{-}_{t-1}	−0.284*	−0.193
Gov^{+}_{t-1}		−0.547**
Gov^{-}_{t-1}		−0.214**
$FBB^{+}\times GOV_{t-1}$		0.137*
$FBB^{-}\times GOV_{t-1}$		−0.168**
$INT^{+}\times GOV_{t-1}$		0.119
$INT^{-}\times GOV_{t-1}$	0.882***	0.614**
URB^{+}_{t-1}	1.214***	1.081***
URB^{-}_{t-1}	-0.439***	-0.485**
GDP^{+}_{t-1}	0.792**	0.713**
GDP^{-}_{t-1}	0.645*	0.487
EN^{+}_{t-1}	1.623***	1.547***
EN^{-}_{t-1}	0.539***	0.637**
REM^{+}_{t-1}	−0.176*	−0.148
REM^{-}_{t-1}	0.476**	0.510*
Short-run		
ΔEF_{t-1}	0.391*	0.498*
ΔFBB^{+}_{t-1}	−0.208*	−0.149
ΔFBB^{-}_{t-1}	0.358**	0.244*
ΔINT^{+}_{t-1}	−0.172	−0.118
ΔINT^{-}_{t-1}		−0.192*
ΔGov^{+}_{t-1}		−0.101*
ΔGov^{-}_{t-1}		0.073
$\Delta FBB^{+}\times GOV_{t-1}$		−0.089*
$\Delta FBB^{-}\times GOV_{t-1}$		0.062
$\Delta INT^{+}\times GOV_{t-1}$	0.417**	0.286*
$\Delta INT^{-}\times GOV_{t-1}$	−0.208*	−0.149
ΔURB^{+}_{t-1}	0.463*	0.401*
ΔURB^{-}_{t-1}	0.386	0.589
ΔGDP^{+}_{t-1}	0.297	0.252
ΔGDP^{-}_{t-1}	0.876	0.790
ΔEN^{+}_{t-1}	0.744**	0.698*
ΔEN^{-}_{t-1}	-0.635*	-0.217*
ΔREM^{+}_{t-1}	−0.082	−0.071
ΔREM^{-}_{t-1}	0.092	-0.321

Notes: ***, **, and * indicate the significance at 1%, 5%, and 10%, respectively.

Table 6 indicates that there is a lot of long-run asymmetry in the association between the ecological footprint and ICT. In the baseline model, it can be seen that positive responses to FBB and INT raise the ecological footprint, but negative responses lower the footprint or are smaller, and Wald tests show that they are asymmetrical. There is high symmetric pressure on energy consumption, and little of the remittances. In the moderated model, governance ability goes on to reduce ecological pressure and considerably abates the effect of ICT as shown by terms of interaction that are statistically significant. Diagnostic tests confirm the adequacy of the model: cointegration is proved, and Portmanteau, heteroskedasticity, Ramsey RESET, and Jarque Bera tests do not show series correlation, a specification error, or non-normality, and, therefore, the soundness and consistency of the NARDL estimates.

Table 6. Asymmetric and model diagnostics

	Long run (+)	Long run (-)	Long run asymmetry (p-value) W_{LR}	Short run asymmetry (p-value) W_{LR}
EF=f(ICT,URB,GDP,EN,REM)				
FBB	0.903***	−0.418**	0.003	0.047
INT	0.768***	−0.301*	0.008	0.092
URB	1.287***	0.944**	0.021	0.118
GDP	0.824**	0.612*	0.033	0.141
EN	1.672***	1.204***	0.004	0.029
REM	−0.214*	−0.136	0.086	0.213
Cointegration			F-Stat	6.958
Portmanteau			_p-value_	0.643
Heteroskedasticity			_p-value_	0.517
Ramsey test			_p-value_	0.372
J-B test			_p-value_	0.688
SEG=f(ICT,INT,GOV,ICT×GOV,URB,GDP,EN,REM)				
FBB	0.642**	−0.271*	0.014	0.071
INT	0.514**	−0.204	0.031	0.104
GOV	−0.556**	−0.392*	0.026	0.083
FBB×GOV	−0.228**	0.156*	0.009	0.052
INT×GOV	−0.179**	0.121	0.018	0.097
URB	1.103***	0.889**	0.041	0.162
GDP	0.739**	0.558*	0.049	0.183
EN	1.594***	1.177***	0.006	0.034
REM	−0.168	−0.112	0.119	0.248
Cointegration			F-Stat	7.432
Portmanteau			_p-value_	0.719
Heteroskedasticity			_p-value_	0.563
Ramsey test			_p-value_	0.409
J-B test			_p-value_	0.731

Notes: ***, **, and * indicate the significance at 1%, 5%, and 10%, respectively

4.5. Discussion

The results show that positive shocks of fixed broadband and internet use augment the ecological footprint in Pakistan, which is the energy-intensive digital growth in a system reliant on fossil fuels. The ecological load of carbon is probably escalated because of increasing ICT infrastructure, whereas thermal generation still has a significant place in the electricity mix in Pakistan (Rehman et al., 2021). The significant positive correlation of energy consumption also supports the fact that environmental degradation is tightly linked with the use of conventional energy, which is also in line with the dependence of Pakistan on imported fossil fuels (Yousaf et al., 2022). Ecological footprint also increases with urbanization and economic growth as an expression of infrastructure development and growth trends that are consumption-based characteristics of emergent economies. On the other hand, better governance minimizes the ecological pressure and the ICT environment relationship since it implies that the stronger the regulatory structure, the better the conformity to environmental regulations and use of resources. This is consistent with the support of the evidence that institutional effectiveness improves the environmental outcomes of developing economies (Dkhili, 2018). The moderating effect of the governance suggests that digitalization would help achieve sustainability when implemented in appropriate regulatory and policy institutions.

5. Conclusion

This paper reveals that the effects of ICT on ecological footprint in Pakistan are institutional and asymmetric. The indicators of digital expansion include the growth of the number of broadband subscriptions and the use of the internet, which exert greater pressure on the environment in the long term, especially because of the reliance on energy sources based on fossil fuels and the scale effects related to the development of the economy and the growth of cities. But these negative impacts can largely be reduced by the quality of governance, which means that the strength of any institution is crucial in shaping digitalization into a force that finds an environmentally accommodating solution. The evidence shows that the NARDL framework is appropriate and emphasizes that sustainable digital changes in Pakistan will not merely rely on technology diffusion but also will be linked with the effective functioning of the regulations and reforms in the energy sector.

The findings imply that the digital expansion strategy of Pakistan would need to be combined with environmental and institutional changes. Policymakers ought to coordinate the development of ICT and the introduction of renewable energy to lower the amount of carbon introduced in the widening broadband infrastructure. The environmental costs of digitalization can be corrected by incentives for energy-efficient data centers, green telecommunications networks, and smart grid technologies. Enhancement of the standard and the capacity to enforce regulatory measures is also very important because the control program in relation to the ICT component combats the effect of ecological pressure significantly. The urban planning policies must encourage environmental stress through sustainable development of the infrastructure to address the population increase. Also, the financial policy, like green taxation and specific subsidies of clean technologies, could guarantee that ICT diffusion would lead to long-term ecological sustainability instead of growth based on resources.

There are various limitations in this study. One, it only considers Pakistan and does not give generalizability across countries. Second, the broadband subscriptions and internet users' proxy ICT, which might be insufficient to reflect digital intensity, activities of data-center or other related emerging technology like cloud computing and artificial intelligence. Third, the regulatory quality is the only measure of governance, which may be inappropriate across the institutional levels. Future studies may use the multi-country panel or regional analysis in order to enhance the external validity. Inclusion of other digitalization practices and renewable energy intensity would perfect the inference. Also, it may be better to implement time-varying or structural breaks in the implementation of the different policy regimes and technological shifts in the developing economies.

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