International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(3), 176-185.

# The Moderating Role of Information and Communication Technology Diffusion in Informal Economy-Pollution Nexus in Kingdom Saudi Arabia

**Naima Sadaoui[1], Lotfi Zabat[2], Mehdi Abid[2]*, Balsam Saeed Abdelrhman Hussien[1]**

[1]Department of Business Management, College of Business, Jouf University, Skaka, Saudi Arabia, [2]Department of Finance and Investment, College of Business, Jouf University, Skaka, Saudi Arabia. *Email: meabid@ju.edu.sa

**Received:** 21 November 2024 **Accepted:** 11 March 2025 **DOI:** https://doi.org/10.32479/ijeep.18501

**ABSTRACT**

This study investigates the moderating role of ICT in the relationship between the informal economy and environmental degradation in Saudi Arabia from 1990 to 2020. Additionally, it identifies the threshold level of ICT necessary to mitigate the impact of the shadow economy and reduce environmental pollution. Using the Autoregressive Distributed Lag (ARDL) approach, the results reveal that the informal economy significantly increases environmental degradation in both the short and long term, while ICT has a negative impact on pollution. This suggests that the informal economy deteriorates environmental quality, whereas ICT helps reduce it. The interaction between the informal economy and ICT shows a negative but statistically insignificant effect on environmental degradation in the long run, indicating that ICT alone is insufficient to achieve a significant reduction in either the informal economy or environmental degradation. Additionally, the study identifies a threshold level of 2.722 for ICT, which is necessary to effectively diminish the impact of the informal economy and reduce environmental degradation. Policymakers should focus on integrating ICT into environmental regulations, strengthening digital systems for monitoring and enforcement. Additionally, regulating the informal economy measures are crucial for effective policy implementation. Promoting digital transformation and public awareness will further support these efforts and help achieve better environmental outcomes.

**Keywords:** Pollution, Informal Economy, Information and Communication Technology, Saudi Arabia
**JEL Classifications:** C1, Q41, Q43

## 1. INTRODUCTION

The issue of climate change due to increasing levels of greenhouse gas emissions is garnering significant attention (Li et al., 2022; Duan, 2023; Franco et al., 2023; Jakučionytė-Skodienė and Liobikienė, 2023). The Rio Summit in 1992 undoubtedly marked the starting point for the awareness of environmental issues. As the stakes have grown increasingly important, the United Nations Framework Convention on Climate Change followed, leading to the Kyoto Protocol agreement in December 1997, the Copenhagen Climate Conference in 2009, the Paris Conference (COP21) held in November-December 2015, and the Germany Conference (COP23) in November 2017. This awareness is equally crucial for the survival of ecological systems in developing countries (DCs). Indeed, environmental degradation is believed to be alleviated by technological progress and economic development (Sirag et al., 2018; Ehigiamusoe et al., 2020).

Moreover, the informal economy can significantly impact $CO_2$ emissions, although this impact is complex and depends on several factors, including geographical context, the nature of informal activities, and the policies in place to regulate and promote sustainability in these sectors. However, it is important to note that the informal economy is not homogeneous, and there

This Journal is licensed under a Creative Commons Attribution 4.0 International License

are significant variations from one region to another. In some cases, the informal economy can also play a positive role by providing employment opportunities to disadvantaged populations. Therefore, it is essential to implement policies aimed at integrating the informal economy into sustainable development initiatives by encouraging the adoption of more environmentally friendly practices and offering cleaner economic alternatives.

Several literatures have been published in recent years on the nexus between informal economy and environmental quality. Nevertheless, the empirical evidence and theoretical underpinnings remain unclear. Theoretically, the mixed effects of the scale and deregulation effects explain the impacts of the informal economy on environmental pollution (Sultana et al., 2022; Chu et al., 2023; Shahbaz et al., 2023; Gheraia et al., 2023). On the one hand, informal economy may contain economic deterioration as they expand due to their small scales and labor-intensive natures. On the other hand, informal economy expansion has been linked to environmental risks due to a lack of regulations. The deregulation effect has been strongly supported by most empirical studies (Harriss-White, 2010; Charlot et al., 2015; Canh et al., 2021; Saha et al., 2021; Dramani et al., 2022; Salinas et al., 2023; Abid et al., 2023), scale effect is also supported by others (Kpognon, 2022; Ndoya et al., 2023; Masca and Chis, 2023). On the other hand, Dewick et al. (2022) and Alvarado et al. (2022) find that both factors have an inverted U-shaped relationship. There is another research strand exploring how the moderator plays a role in such relationships, motivated by the inconsistent findings in empirical studies of the environmental impacts of the informal economy. The deregulation in the informal economy is intensified by weak institutions, tax increases, and stringent environmental regulations (Elbahnasawy, 2021; Nguyen, 2022; Chu and Hoang, 2022). However, the development of the information and communication technology (ICT) is an important indicator of the economic development of each state (Niebel, 2018; Stanley et al., 2018; Appiah-Otoo and Song, 2021; Ajide and Dada, 2022; Harkat et al., 2022). ICT can contribute in various ways to supporting the three main pillars of the Bali Action Plan, which was developed during the thirteenth Conference of the Parties in December 2007. These pillars focus on enhanced action for adaptation, coordinated action for reducing greenhouse gas (GHG) emissions, and measures for mitigating climate change. Additionally, ICT can be leveraged to mitigate the impact of other sectors on GHG emissions and to assist countries in adapting to climate change.

Chu and Hoang (2022) investigated the factors affecting ecological footprint, including the informal economy, trade openness, energy intensity, renewable energy, and income in OECD countries. The findings suggest that the impact of the informal economy on the environment is not consistent across different levels of ecological footprint. A higher size of the informal economy leads to more ecosystem degradation, but beyond certain thresholds, it can have environmental benefits. The study also confirms a one-way relationship from the informal economy to the ecological footprint. Overall, the study establishes significant and diverse relationships between ecological footprint and its determining factors. Alvarado et al. (2022) studied the influence of the informal economy, urban concentration, and globalization on the ecological footprint for 95 countries from 1990 to 2018. Their findings reveal a sustained connection between these factors, with the long-term impact of the informal economy on the ecological footprint being greater than the short-term impact. Moreover, the causality analysis suggests limited causal relationships between the informal economy, urban population, globalization, and the ecological footprint, emphasizing the need for differentiated strategies to mitigate ecological footprints in the long-term. Sultana et al. (2022) examined the relationship between informal economy, $CO_2$ emissions, ecological footprints, and NO emissions in 15 emerging countries from 2002 to 2019. Their empirical analysis reveals that informal economy have a positive impact on environmental quality, reducing $CO_2$ emissions and ecological footprints, while negatively affecting NO emissions. Shahbaz et al. (2023) examined the impact of informality, institutional quality, and renewable energy consumption on ecological footprint for emerging Europe and Asia countries from 2002 to 2018. They found that informality has positive effects on ecological footprint in the long run for emerging European countries, while the effect is negative for emerging Asian countries.

Ndoya et al. (2023) studied the impact of ICT on the informal economy for 45 African countries from 2000 to 2017. Their results show that financial development play a role in mediating the effects of ICT on the informal economy. Nevertheless, Garcia-Murillo and Velez-Ospina (2017) indicated that ICT leads to a decrease in the transaction costs of informal firms. In contrast, Remeikien et al. (2022) studied the effect of ICT on the informal economy in 11 European Union countries. They discovered that ICT tend to reduce informal economy, whatever the period. According to Ajide and Dada (2022), ICT and informal economy are linked bidirectionally in West African countries, on the one hand, and that ICT only decrease informal economy in certain quintiles of countries, on the other hand.

Islam et al. (2023) tested the nexus between ICT and $CO_2$ emissions in GCC countries during the 1995-2019 period. They prove that the relationship between these two variables is asymmetrical and $CO_2$ emissions are reduced by ICT shocks. Usman et al. (2021) studied the impact of ICT on $CO_2$ emissions in nine economies in Asia. They found that the asymmetry impacts on the effect of increased and decreased ICT was supported in both the short and long run. Similarly, Kahouli et al. (2022) study the impact of ICT on environmental quality in Saudi Arabia. Their results indicate that there is a significant and negative relation between ICT and ecological footprints in the short-term. In addition, in the 10 nations with the highest pollution levels, Caglar et al. (2021) analyzed the impact of renewable and non-renewable energy consumption, GDP, financial development, and ICT on ecological footprints. Their results shows that renewable energy, ICT, and financial development have a positive effect on the environmental quality in these countries. Several studies, however, have concluded that ICT create harmful effects on the environmental quality. For example, from 1991 to 2009, Lee and Brahmasrene (2014) confirmed the positive impact of ICT on $CO_2$ emissions in ASEAN countries. In addition, Zhang and Liu (2015) found that the use of ICT in China was positively related to carbon emissions between 2000 and 2010.

The conditional hypothesis suggests that the relationship between two variables can be influenced by another variable (Brambor et al., 2006; Ehigiamusoe et al., 2019). A multiplicative interaction model is used to identify the relationship between two variables (e.g. informal economy and $CO_2$ emissions) in order to capture the moderating impact of one variable (e.g. ICT diffusion). There are several models that can be used to test the unconditional hypothesis, including the linear and quadratic model. However, the multiplicative interaction model is more suitable to test the conditional hypothesis because it explains how one variable can influence the relationship between two other variables. Several empirical and theoretical studies have shown that multiplicative interaction models can effectively capture the intuition behind conditional hypotheses (Ehigiamusoe and Lean, 2020; Friedrich, 1982). At different levels of the variable (ICT), multiple interaction model can also identify the marginal effect of informal economy on ecological footprints.

In our study, we asked the question: How does ICT moderate the impact of informal economy on $CO_2$ emissions? In particular, we tested the hypothesis that informal economy has a larger marginal effect on $CO_2$ emissions when it is applied to a higher level of ICT rather than to a lower level. This is consistent with a growing body of research both theoretically and empirically that suggests that high levels of ICT can not only expedite informal economies, but can also exacerbate $CO_2$ emissions (Hossain, 2011; Narayan and Smyth, 2008). It is expected that the simultaneous increase in ICT use and informal economy will exacerbate $CO_2$ emissions. It is also important to note, nevertheless, higher ICT penetration may not affect the environment adversely if there are higher levels of ICT diffusion (Hossain, 2011).

As far as we know, there has never been a study that has examined this question in terms of multiplicative interaction models before. By including ICT as one of the factors affecting $CO_2$ emissions, Elgin and Oztunali (2014) argued that the response of ecological footprints to informal economy and the turning point of the EKC are underestimated. Nevertheless, Chatti and Majeed (2023) discussed that Elgin and Oztunali's (2014) conclusions on the relationship between informal economy and ecological footprints are sensitive to the assumed form. It has been observed that GDP by itself may not be an effective means of curbing pollution by itself (Soytas et al., 2007). In consequence, models without multiplicative interaction terms may not adequately capture the dynamic relationship between ICT, informal economy, and ecological footprints. Due to these reasons, we use both quadratic and multiplicative interaction models to test for the existence of the EKC.

This paper contributes to the literature in several ways. Firstly, it is the only study to adopt multiplicative interaction models in order to test the EKC hypothesis. Secondly, this is the first systematic investigation of the moderating role of ICT on the $CO_2$ emissions - informal economy nexus. Thirdly, our study is the first to demonstrate the marginal effects of informal economy on $CO_2$ emissions at varying levels of ICT diffusion. Fourthly, we include the kingdom Saudi Arabia (KSA) in our study, a country that has been neglected in previous researches. In KSA country, increasing levels of $CO_2$ emissions will require policies to address their increasing levels. The empirical results of this study will be valuable for formulating such policies. If ICT diffusion moderates the impact of informal economy on $CO_2$ emissions, this implies that an appropriate interaction of ICT and informal economy could mitigate $CO_2$ emissions. Consequently, if the levels of ICT diffusion and informal economy are simultaneously changed, then the increasing levels of $CO_2$ emissions may be at least partially addressed.

In the remainder of this paper, we will follow the following structure. The model specifications are detailed in Section 2. Methodology and data are presented in Section 3, while empirical findings are provided in Section 4. Conclusions and future research suggestions are provided in Section 5.

## 2. MODEL SPECIFICATION

This paper primarily aims to explore the impact of ICT diffusion on the relationship between the shadow economy and environmental pollution in Saudia Arabia. To achieve this, it employs a modified Environmental Kuznets Curve (EKC) framework that integrates ICT diffusion and the shadow economy as critical factors influencing environmental outcomes. The EKC framework offers a valuable foundation for analyzing the relationship between economic and environmental variables within an economic context, addressing contemporary issues such as global pollution and the presence of a shadow economy. The present study considers the following equation:

$$CO2_t = F\,(GDP_t, \mathrm{IF}_t, \mathrm{ICT}_t, \mathrm{Z}_t) \tag{1}$$

Where ENV represents environmental pollution, GDP stands for per capita income, IF denotes the informal economy, ICT refers to Information and Communications Technology, and Z includes other control variables that influence environmental pollution. This model also includes population density and trade openness as additional control variables. The model is specifically defined as follows:

$$CO2_t = \alpha_0 + \alpha_1\, GDP_t + \alpha_2\, \mathrm{IF}_t + \alpha_3\, \mathrm{ICT}_t + \alpha_4\, \mathrm{POP}_t + \alpha_5\, TOP_t + \varepsilon_t \tag{2}$$

Where POP represents population density, TOP denotes trade openness, and ε is the error term. To account for the moderating role of ICT in the relationship between the shadow economy and environmental impact, an interaction term between the shadow economy and ICT is included in equation (2).

$$CO2_t = \alpha_0 + \alpha_1\, GDP_t + \alpha_2\, \mathrm{IF}_t + \alpha_3\, \mathrm{ICT}_t + \delta(\mathrm{IF} \times \mathrm{ICT})_t + \alpha_4\, \mathrm{POP}_t + \alpha_5\, TOP_t + \varepsilon_t \tag{3}$$

Accordingly, the a priori expectation is that the informal economy will have a significant and positive impact on environmental pollution, due to its critical role as a major pollution determinant in developing countries (Sahay and Ranjana, 2024). This indicates that the informal economy deteriorates environmental quality in Saudi Arabia. The coefficient of ICT is anticipated to have a negative effect on environmental pollution when strong institutions are present, whereas a positive effect is expected in the presence of weak institutions. This suggests that ICT infrastructure and internet access are crucial tools for achieving sustainable development in Saudi Arabia. Regarding the interaction term between the informal economy and ICT, a significant negative coefficient indicates that strong institutional quality reduces environmental pollution by decreasing the informal economy. Conversely, a significant positive coefficient for the interaction term indicates that weak ICT infrastructure fosters the informal economy, which in turn contributes to increased environmental pollution. The coefficient for per capita income is anticipated to significantly and positively influence environmental pollution. The effect of population density and trade openness on environmental pollution is uncertain. While increased population density in industrialized areas may exacerbate pollution, it could also drive governments to enforce stricter environmental regulations, potentially reducing pollution. Trade openness is expected to have a negative effect on environmental pollution if clean technologies are used, leading to reduced pollution and waste emissions. Conversely, if outdated or harmful technologies are employed, trade openness could have a positive effect, increasing pollution and waste emissions.

## 3. DATA AND METHODOLOGY

This study investigates the moderating effect of ICT diffusion on the relationship between the informal economy and $CO_2$ emissions in Saudia Arabia from 1990 to 2020. The $CO_2$ emissions per capita measured in metric tons. GDP per capita (measured in constant 2017 international \$). Trade openness is calculated as the sum of exports and imports expressed as a percentage of GDP. Population density is measured by the number of individuals per unit of geographic area. The informal economy (IF) is measured using the MIMIC (Multiple Indicators Multiple Causes) and DGE (Dynamic General Equilibrium) techniques, as applied by Elgin et al. (2021). The study captures ICT using three variables: fixed telephone subscriptions per 100 people (FT), internet usage as a percentage of the population (IU), and mobile cellular subscriptions per 100 people (MCS). These data are sourced from the World Development Indicators. We employ Principal Component Analysis (PCA) to construct a ICT index. PCA is primarily utilized to address the challenges of multicollinearity and to preserve the degrees of freedom in the analysis.

This paper aims to analyze both long-term and short-term dynamics through a time series dataset of the variables. The ARDL technique is particularly suitable for this study because it does not require prior knowledge of the variables' properties. It can be applied regardless of the variables' order of integration, as long as it is no more than one (I[1]). Additionally, the ARDL method is effective even with a small period for the series (Dada, 2019). The ARDL approach also provides unbiased estimates of both short- and long-run dynamics in a single-step process. In accordance with Pesaran et al. (2001), equation (3) is reformulated to assess both long- and short-run effects simultaneously using the bounds testing approach:

$$\Delta CO2_t = \alpha_0 + \sum_{J=0}^{K}\rho_j \Delta CO2_{t-j} + \sum_{J=0}^{m}\theta_j \Delta GDP_{t-j} + \sum_{J=0}^{n}\gamma_j \Delta IF_{t-j} + \sum_{J=0}^{r}\lambda_j \Delta ICT_{t-j} + \sum_{J=0}^{P}\eta_j \Delta(ICT\times \mathrm{IF})_{t-j} + \sum_{J=0}^{s}\kappa_j \Delta POP_{t-j} + \sum_{J=0}^{r}\nu_j \Delta TOP_{t-j} + \beta_0 CO2_{t-1} + \beta_1 GDP_{t-1} + \beta_2 IF_{t-1} + \beta_3 ICT_{t-1} + \beta_4 (IF\times ICT)_{t-1} + \beta_5 POP_{t-1} + \beta_6 TOP_{t-1} + \varepsilon_t \quad (4)$$

the coefficients associated with the differenced variables represent short-term effects, whereas the coefficients of the level variables " $\beta_j$" represent long-term effects.

In equation (4), the long-run coefficients are normalized relative to environmental pollution. The normalized equation is presented as follows:

$$CO2_{t-1} = \theta_1 + \theta_2 GDP_{t-1} + \theta_3 \mathrm{IF}_{t-1} + \theta_4 \mathrm{ICT}_{t-1} + \theta_5 (\mathrm{IF}\times\mathrm{ICT})_{t-1} + \theta_6 \mathrm{POP}_{t-1} + \theta_7 TOP_{t-1} + \omega_t \quad (5)$$

Where, $\theta_1 = \frac{\alpha_0}{-\beta_0}$, $\theta_2 = \frac{\beta_1}{-\beta_0}$, $\theta_3 = \frac{\beta_2}{-\beta_0}$, $\theta_4 = \frac{\beta_3}{-\beta_0}$, $\theta_5 = \frac{\beta_4}{-\beta_0}$, $\theta_6 = \frac{\beta_5}{-\beta_0}$ and $\theta_7 = \frac{\beta_6}{-\beta_0}$

The long-run marginal effect of ICT on the relationship between the informal economy and $CO_2$ emissions can be derived by partially differentiating equation (5) with respect to the informal economy and setting the result equal to zero (Huynh, 2020).

$$\frac{\partial CO2_{t-1}}{\partial IF_{t-1}} = \theta_3 + \theta_5 ICT_{t-1} \quad (6)$$

If the two parameters ($\theta_3$, $\theta_5$) in equation (6) have alternating signs, it indicates that the threshold level of ICT can be determined. By setting equation (6) to zero, the threshold level is identified, which diminishes the influence of the informal economy and helps to reduce environmental pollution in Saudia Arabia.

$$ICT_{t-1} = \frac{\theta_3}{-\theta_5} \quad (7)$$

## 4. RESULTS AND DISCUSSION

Given that the autoregressive distributed lag (ARDL) technique requires variables to be stationary either at level (I[0]) or first difference (I[1]), a unit root test was conducted on all variables to determine their stationarity. The results, summarized in Table 1, indicate that the variables exhibit stationarity at either I(0) or I(1). Specifically, $CO_2$ emissions, the informal economy, per capita income, and population density are stationary at first difference

**Table 1: Results from the unit root tests**

| Statistic | Level | | | | | |
|---|---|---|---|---|---|---|
| | $CO_2$ | TR | ICT | IF | POP | GDP |
| ADF | −1.037 | −4.102** | −2.140 | −3.684** | −0.213 | −1.384 |
| PP | −1.127 | −5.007*** | −1.192 | −6.098*** | −1.188 | −1.367 |
| **Statistic** | **First difference** | | | | | |
| ADF | −7.012*** | - | −5.087*** | - | −5.206*** | −5.364*** |
| PP | −7.124*** | - | −6.210*** | - | −6.387*** | −5.546*** |

Significant levels of 1%, and 10% are represented by ***, and *

according to both the augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests, while IF and trade openness are stationary at level. Since the variables are a mix of I(0) and I(1), and notably, the dependent variable is stationary at first difference, the ARDL technique is appropriately chosen for estimation.

Table 2 displays the results of the ARDL cointegration bounds test, which employs the F-test (Pesaran, et al., 2001; Narayan, 2005) to evaluate whether the variables are cointegrated. The null hypothesis posits that no cointegration is present. However, with a calculated F-statistic of 4.55, which surpasses the upper critical value at I(1), the analysis confirms the presence of cointegration among the variables.

After confirming the existence of a long-run relationship among the variables through the ARDL bounds test, Table 3 presents the short- and long-run moderating effects of ICT on the informal economy–environmental degradation nexus, along with the relevant diagnostic statistics. The informal economy exerts a positive and significant influence on environmental degradation, both in the short term and long term. This suggests that the informal economy plays a role in driving environmental degradation, with its expansion contributing to increased pollution levels in Saudia Arabia. This means that activities within the informal sector, which are often unregulated and unreported, contribute to environmental harm such as increased pollution and resource depletion. The significance of this effect indicates that the relationship between the informal economy and environmental degradation is robust and not merely coincidental. Furthermore, the adverse impact of the informal economy on the environment persists over time, affecting environmental quality both immediately and in the long run. This highlights the ongoing challenge of managing and mitigating the environmental consequences of informal economic activities. In terms of magnitude, the coefficient of the informal economy is greater in the long run compared to the short run. The outcome of this study aligns with both theoretical and empirical findings presented by Qayyum et al. (2021) and Chu (2022). Their research supports the observation that the informal economy contributes significantly to environmental degradation, reinforcing the conclusions drawn in this study.

The results indicate that ICT (Information and Communication Technology) has a negative impact on environmental quality, meaning that as ICT usage increases, environmental degradation decreases. This suggests that ICT plays a role in improving environmental outcomes, possibly through more efficient resource management, reduced need for physical infrastructure, or innovations that minimize environmental harm. However, the results also show that this negative impact is not significant in the short run. This lack of significance suggests that the immediate effects of ICT on the environment are not strong enough to be statistically confirmed, possibly due to the initial investment and implementation phases of ICT technologies, where the benefits to environmental quality may not be immediately apparent.

**Table 2: ARDL cointegration bounds test results**

| Test statistic | Value | K |
|---|---|---|
| F-statistic | 4.55 | |
| Critical value bounds | | |
| **Significance (%)** | **I (0)** | **I (1)** |
| 10 | 2.10 | 3.17 |
| 5 | 2.34 | 3.46 |
| 1 | 3.51 | 4.12 |

Source: Author calculation

**Table 3: Regression results for moderating effect of ICT in informal economy–environmental degradation nexus**

| Independent variables | Coefficient | Standard error | P-value |
|---|---|---|---|
| Short run | | | |
| ΔIF | 0.022*** | 0.062 | 0.000 |
| ΔICT | −0.320 | 0.964 | 0.126 |
| Δ(IF × ICT) | 0.004*** | 0.068 | 0.007 |
| ΔGDP | 0.003** | 0.088 | 0.035 |
| ΔTOP | 0.007* | 0.097 | 0.075 |
| ΔPOP | 0.624 | 0.214 | 0.315 |
| ΔPOP (−1) | −2.049*** | 0.081 | 0.001 |
| ECT (−1) | −0.820*** | 0.053 | 0.000 |
| Long run | | | |
| IF | 0.042*** | 0.057 | 0.000 |
| ICT | −0.274** | 0.029 | 0.046 |
| (IF × ICT) | −0.016 | 0.231 | 0.428 |
| GDP | 0.005** | 0.075 | 0.012 |
| TOP | 0.003* | 0.094 | 0.082 |
| POP | 0.098*** | 0.076 | 0.001 |
| Constant | 5.135*** | 0.069 | 0.000 |
| Threshold value of ICT | | | 2.722 |
| Diagnostic tests | | | |
| $R^2$ | | | 0.824 |
| *F*-statistic (prob) | | | 0.000 |
| Jarque–Bera test | | | 0.587 |
| White homoscedasticity test | | | 0.317 |

***, **and* indicate the statistical significance at the 1, 5% and 10% levels, respectively

In contrast, the long-run impact of ICT on environmental quality is more pronounced and statistically significant. Over time, the adoption and integration of ICT may lead to more substantial improvements in environmental quality, as the technologies become more widespread and their environmental benefits are fully realized. In summary, while ICT has the potential to positively influence environmental quality, this effect is more evident in the long run, with short-term impacts being less conclusive.

In comparison with previous studies, the results of this study are consistent with the findings of various researchers who have examined the relationship between ICT and environmental quality. For instance, the long-run negative impact of ICT on environmental degradation aligns with the conclusions of studies like Higón et al. (2017), who found that ICT adoption can lead to more sustainable environmental practices by improving energy efficiency and reducing carbon footprints over time. However, the insignificance of the short-run impact contrasts with findings from other studies, such as those by Khan et al. (2020), which reported that ICT could have an immediate positive effect on reducing environmental degradation. This discrepancy might be attributed to differences in the scope of ICT development across regions, varying levels of ICT infrastructure maturity, or different methodologies used in assessing the short-run effects.

Furthermore, the results suggest a complex relationship between ICT, the informal economy, and environmental pollution. In the short run, the interaction between ICT and the informal economy (ICT × IF) has a significant positive effect on environmental pollution. This means that when ICT development occurs alongside a thriving informal economy, it initially leads to increased environmental degradation. One possible explanation is that ICT might facilitate activities within the informal economy, such as unregulated industries or informal sectors, which can intensify pollution due to the lack of oversight and environmental regulations. However, in the long run, the interaction between ICT and the informal economy shows a negative but statistically insignificant effect on environmental pollution. This indicates that over time, ICT may begin to play a role in mitigating the negative environmental impacts of the informal economy, possibly through increased efficiency, better resource management, or the gradual integration of these informal sectors into the formal economy, where environmental regulations are stricter. Nonetheless, the fact that this long-run effect is not statistically significant suggests that the mitigating influence of ICT on environmental pollution within the informal economy may not be strong or consistent enough to be definitively proven across all contexts.

When compared to previous studies, the results of this study reveal both alignment and divergence. The significant positive effect of the ICT-shadow economy interaction on environmental pollution in the short run is consistent with findings from Chatti and Majeed (2022), who suggest that ICT can intensify environmental degradation when used in unregulated informal sectors. However, the study's finding of a negative but statistically insignificant long-run effect contrast with research by Zheng et al. (2023), which demonstrates that over time, ICT adoption tends to mitigate environmental harm, even within economies with substantial shadow sectors. The lack of significance in the long-run effect also echoes the observations of Zhu et al. (2013), who note that the long-term environmental benefits of ICT are highly context-dependent, varying with levels of regulation and economic development. This suggests that while ICT has the potential to reduce environmental pollution in the long term, its effectiveness may be limited by other factors, such as the regulatory environment and the degree of ICT integration.

Additionally, the coefficients of the other control variables exhibit mixed effects on environmental pollution, each of which is examined individually. For instance, per capita income shows a significant positive impact on environmental pollution in Saudi Arabia. This indicates that as individuals' income rises, their consumption levels also increase, leading to higher demand for goods and services. Consequently, this surge in consumption drives up production levels, which in turn escalates environmental pollution due to increased industrial activity and resource use. This finding aligns with the Environmental Kuznets Curve hypothesis, where economic growth initially leads to greater environmental degradation before potentially improving as higher income levels enable investment in cleaner technologies and stricter environmental regulations. This result aligns with the findings of Wang et al. (2024a) and Wang et al. (2024b). Both studies similarly observed that increases in per capita income can lead to heightened environmental pollution, particularly in the early stages of economic growth. As income rises, the demand for goods and services escalates, driving up production and consequently increasing pollution levels. This outcome supports the notion that economic development often comes at the cost of environmental quality, at least initially, before potentially leading to improvements as economies mature and adopt more sustainable practices.

Similarly, trade openness demonstrates a significant positive effect on environmental pollution. This suggests that as Saudi Arabia increases its participation in international trade, the associated rise in industrial activity, transportation, and resource extraction contributes to greater environmental degradation. The influx of foreign goods and services, coupled with increased export activities, likely amplifies pollution levels due to higher production demands and the environmental impact of shipping and logistics. This finding is consistent with the pollution haven hypothesis, which posits that countries with less stringent environmental regulations may experience increased pollution as they engage more actively in global trade. The significant positive effect of trade openness on environmental pollution observed in this study is consistent with findings from previous research. Studies by Ghazouani and Maktouf (2024) and Wang et al. (2024c) similarly report that increased trade openness can lead to greater environmental degradation, particularly in developing economies like Saudi Arabia. These studies suggest that as countries engage more in global trade, the associated rise in industrial activity and resource extraction intensifies pollution, especially in regions where environmental regulations may be less stringent. This aligns with the pollution haven hypothesis, which posits that countries with weaker environmental policies may attract pollution-intensive industries.

While some research, such as that by Antweiler et al. (2001), indicates that trade can have mixed effects on the environment, the context of Saudi Arabia—characterized by resource-intensive industries—seems to amplify the adverse impact of trade openness on environmental quality.

Population density exerts a complex influence on environmental pollution, displaying a negative effect in the short run but shifting to a positive effect in the long run. In the short term, higher population density might lead to more efficient use of resources and infrastructure, potentially reducing per capita pollution levels due to economies of scale and shared services. However, as time progresses, the positive impact of population density on pollution emerges, likely due to the increasing strain on resources, infrastructure, and public services. Overcrowding can lead to higher waste production, greater energy consumption, and intensified industrial activity to meet the demands of a growing population, ultimately escalating environmental degradation in the long run. This transition reflects the dual-edged nature of population growth, where initial benefits of density give way to the environmental costs associated with sustaining larger populations over time. This finding aligns with the research conducted by Chen et al. (2018), who also identified a direct relationship between population density and environmental pollution. They observed that as population density increases, the pressure on natural resources and infrastructure intensifies, leading to higher levels of pollution over time. Their work supports the idea that while densely populated areas may initially benefit from more efficient resource use, the long-term effects often include heightened environmental degradation as the demands of a growing population outpace the capacity for sustainable management.

Regarding the diagnostic indicators, the error correction term (ECT) is both negative and statistically significant, indicating that the model effectively reverts to its long-run equilibrium after short-term deviations. This is a crucial sign of model stability and suggests that any shocks to the system are corrected over time. Moreover, the model demonstrates robustness by being free from heteroskedasticity issues, as confirmed by diagnostic tests. The Jarque–Bera test results further validate the normality of the residuals, ensuring that the model's assumptions hold. The adjusted R-square value indicates that the model explains 79% of the variation in the dependent variable, showcasing strong explanatory power. Additionally, the F-statistic value of 10.33 confirms the overall statistical significance of the model, implying that the included variables collectively have a meaningful impact on the outcome. The stability of the model coefficients is further supported by the CUSUM and CUSUM of squares tests, as depicted in Figures 1 and 2, which show that the model's coefficients remain stable over time. These results collectively suggest that the model is both reliable and robust, allowing for valid inferences to be drawn, consistent with the findings of Dada and Abanikanda (2019).

To identify the threshold level of ICT in the relationship between the informal economy and environmental degradation, this study follows the methodology employed in previous research, such as those by Uyar et al. (2021), Dossou et al. (2023), and Erumban (2024). Specifically, the normalized long-run model, as represented in equation (5), is differentiated with respect to the informal economy, and the result is set equal to zero. This approach allows for the determination of the critical ICT level at which the impact of the informal economy on environmental degradation changes, providing insights into the moderating role of ICT in this relationship.

**Figure 1:** Plot of cumulative sum (CUSUM) of recursive residuals

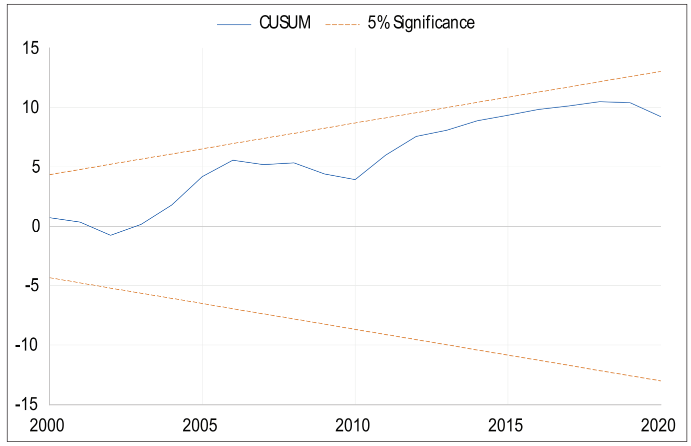
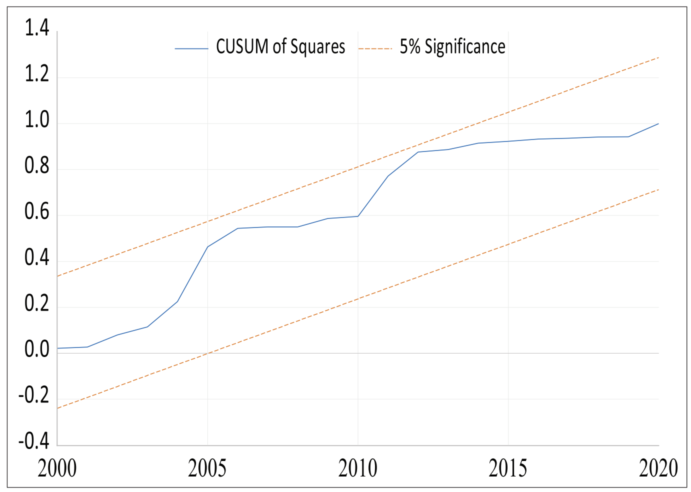



**Figure 2:** Plot of cumulative sum (CUSUM) of squares of recursive residuals




$$\frac{\partial CO2_{t-1}}{\partial IF_{t-1}} = \theta_3 + \theta_5 ICT_{t-1} = 0.030 - 0.011 ICT_{t-1} = 0 \quad (8)$$

The threshold level of 2.72 for ICT in Saudi Arabia, as indicated by equation (8), represents a critical benchmark that must be met or exceeded for ICT to play a significant role in mitigating the effects of the informal economy and reducing environmental degradation. This threshold signifies the minimum level of ICT infrastructure, usage, and integration necessary for the technology to be effective in addressing these challenges. If ICT development remains below this threshold, its ability to influence and improve environmental outcomes may be limited. For instance, insufficient ICT infrastructure could lead to inadequate data collection, poor monitoring of environmental practices, and weak enforcement of regulations related to the informal economy. This could allow environmentally harmful activities to continue unchecked, contributing to greater pollution and resource depletion. On the other hand, when ICT levels surpass the threshold of 2.72, it indicates that the necessary technological tools and systems are in place to support environmental protection efforts. Advanced ICT can facilitate better monitoring of industrial activities, enhance transparency in economic transactions, and improve the efficiency of resource management. It can also enable more effective communication and coordination between regulatory bodies, businesses, and the public, thereby fostering a more sustainable economic environment.

In summary, the threshold of 2.72 is not just a numerical value; it represents a tipping point where ICT transitions from being a passive factor to an active enabler of environmental sustainability. Exceeding this threshold ensures that ICT can contribute meaningfully to reducing the environmental impact of the informal economy, helping Saudi Arabia move towards a more sustainable future.

## 5. CONCLUSION AND POLICY IMPLICATIONS

This study distinguishes itself from existing research in environmental literature by adapting the traditional Environmental Kuznets Curve framework to incorporate the informal economy and ICT factors. Specifically, it investigates how ICT influences the relationship between the informal economy and environmental degradation in Saudi Arabia, covering the period from 1990 to 2020. This novel approach provides a more comprehensive understanding of how technological advancements and informal economic activities interact to affect environmental outcomes. Additionally, the study identifies the threshold level of ICT necessary to effectively reduce the impact of the informal economy and mitigate environmental pollution. By determining this threshold, the research highlights the minimum level of ICT development needed for it to significantly influence and improve environmental outcomes.

The findings of this study indicate that the informal economy exerts a significant positive impact on environmental pollution in Saudi Arabia. This suggests that activities within the informal sector contribute substantially to environmental degradation, exacerbating pollution levels. Consequently, it is crucial for the government to implement stricter monitoring and regulatory measures to minimize the prevalence of informal economic activities. Additionally, improvements in the ease of doing business and the reduction of bureaucratic barriers to business start-ups are necessary to encourage informal sector participants to transition into the formal economy. Such measures are essential as informal sector activities often lack environmental oversight and contribute negatively to environmental quality. Furthermore, increasing environmental awareness among the public is vital to foster more sustainable practices and support regulatory efforts.

In Saudi Arabia, ICT has a negative but statistically insignificant effect on environmental pollution in both the short and long run. This suggests that, despite its potential benefits, ICT does not have a substantial impact on reducing pollution in the immediate or extended timeframe. Conversely, the interaction between the informal economy and ICT exhibits varying effects on environmental pollution depending on the time horizon. In the short run, the presence of informal economic activities, combined with the influence of ICT, appears to exacerbate environmental pollution. This is because institutions may inadvertently support the informal economy, leading to increased pollution. However, in the long run, ICT has the potential to reduce environmental pollution by decreasing the size and impact of the informal economy. Despite this potential, the effect of this interaction on reducing pollution is not statistically significant in the long term. This indicates that while ICT may contribute to mitigating pollution by reducing informal economic activities over time, its impact is not strong enough to be considered significant within the study period. These imply that the current level of ICT in Saudi Arabia is insufficient, as evidenced by the threshold value derived from this study. Improving ICT infrastructure could significantly reduce the adverse effects of the informal economy on environmental pollution. To achieve this, the government should focus on establishing a robust and advanced digital infrastructure that accelerates the digital transformation process. This effort supports the Kingdom’s Vision 2030, which aims to enhance the communications and information technology sector to foster a digital society, a digital government, a thriving digital economy, and an innovative future. Additionally, it is crucial for the government to develop and implement effective environmental laws to address pollution. These regulations should be enacted at all levels of government, with particular emphasis on local implementation, as local authorities are better positioned to address environmental issues at the grassroots level.

This study has provided valuable insights into the relationship among ICT, the informal economy, and environmental pollution. However, it is important to consider its limitations. Due to constraints in data availability, the study uses annual aggregate data for $CO_2$ emissions and the shadow economy, which could be more informative if disaggregated into components from various sectors. Unfortunately, such detailed data is not available for Saudi Arabia. Despite these limitations, the findings remain relevant and contribute significantly to the understanding of the studied relationships. Future research could build on this work by utilizing disaggregated data from developing countries to provide a more detailed analysis.

## ACKNOWLEDGMENTS

This work was funded by the Deanship of Graduate Studies and Scientific Research at Jouf University under grant No (DSR-2023-03-02120).

## 6. REFERENCES

Abid, M., Sekrafi, H., Gheraia, Z., Abdelli, H. (2024), Regulating the unobservable: The impact of the environmental regulation on informal economy and pollution. Energy and Environment, 35(7), 3463-3482.

Ajide, F.M., Dada, J.T. (2022), The impact of ICT on shadow economy in West Africa. International Social Science Journal, 72(245), 749-767.

Alvarado, R., Tillaguango, B., Murshed, M., Ochoa-Moreno, S., Rehman, A., Işık, C., Alvarado-Espejo, J. (2022), Impact of the informal economy on the ecological footprint: The role of urban concentration and globalization. Economic Analysis and Policy, 75, 750-767.

Antweiler, W., Copeland, B.R., Taylor, M.S. (2001), Is free trade good for the environment? American Economic Review, 91(4), 877-908.

Appiah-Otoo, I., Song, N. (2021), The impact of ICT on economic growth-Comparing rich and poor countries. Telecommunications Policy, 45(2), 102082.

Brambor, T., Clark, W.R., Golder, M. (2006), Understanding interaction models: Improving empirical analyses. Political Analysis, 14(1), 63-82.

Caglar, A.E., Mert, M., Boluk, G. (2021), Testing the role of information and communication technologies and renewable energy consumption in ecological footprint quality: Evidence from world top 10 pollutant footprint countries. Journal of Cleaner Production, 298, 126784.

Canh, N.P., Schinckus, C., Thanh, S.D., Chong, F.H.L. (2021), The determinants of the energy consumption: A shadow economy-based perspective. Energy, 225, 120210.

Charlot, O., Malherbet, F., Terra, C. (2015), Informality in developing economies: Regulation and fiscal policies. Journal of Economic Dynamics and Control, 51, 1-27.

Chatti, W., Majeed, M.T. (2022), Information communication technology (ICT), smart urbanization, and environmental quality: Evidence from a panel of developing and developed economies. Journal of Cleaner Production, 366, 132925.

Chatti, W., Majeed, M.T. (2023), How does ICT affect the shadow economy towards environmental preservation? Evidence from a panel of developing and developed nations. Environmental Science and Pollution Research, 30(8), 22046-22062.

Chen, H., Hao, Y., Li, J., & Song, X. (2018), The impact of environmental regulation, shadow economy, and corruption on environmental quality: Theory and empirical evidence from China. Journal of Cleaner production, 195, 200-214.

Chu, L.K. (2022), The impact of informal economy on technological innovation-ecological footprint nexus in OECD countries: New evidence from panel quantile regression. Journal of Environmental Studies and Sciences, 12(3), 515-533.

Chu, L.K., Doğan, B., Ghosh, S., Shahbaz, M. (2023), The influence of shadow economy, environmental policies and geopolitical risk on renewable energy: A comparison of high-and middle-income countries. Journal of Environmental Management, 342, 118122.

Chu, L.K., Hoang, D.P. (2022), The shadow economy-environmental quality nexus in OECD countries: Empirical evidence from panel quantile regression. Environmental Science and Pollution Research, 29(43), 65233-65258.

Dada, M. A. (2019), Disaggregated analysis of foreign trade impact on economic growth; Reflecting on the Nigeria experience. Journal of Economics, Management and Trade, 22(6), 1-15.

Dada, J.T., Abanikanda, E.O. (2019), How important is oil revenue in Nigerian growth process? Evidence from a threshold regression. International Journal of Sustainable Economy, 11(4), 364-377.

Dewick, P., De Mello, A.M., Sarkis, J., Donkor, F.K. (2022), The puzzle of the informal economy and the circular economy. Resources, Conservation and Recycling, 187, 106602.

Dossou, T.A.M., Kambaye, E.N., Berhe, M.W., Asongu, S.A. (2023), Moderating effect of ICT on the relationship between governance quality and income inequality in sub-Saharan Africa. Information Development, 02666669231170396.

Dramani, J.B., Frimpong, P.B., Ofori-Mensah, K.A. (2022), Modelling the informal sector and energy consumption in Ghana. Social Sciences and Humanities Open, 6(1), 100354.

Duan, Z. (2023), Impact of climate change on the life cycle greenhouse gas emissions of cross-laminated timber and reinforced concrete buildings in China. Journal of Cleaner Production, 395, 136446.

Ehigiamusoe, K.U., Lean, H.H. (2020), The role of deficit and debt in financing growth in West Africa. Journal of Policy Modeling, 42(1), 216-234.

Ehigiamusoe, K.U., Lean, H.H., Lee, C.C. (2019), Moderating effect of inflation on the finance-growth nexus: Insights from West African countries. Empirical Economics, 57, 399-422.

Ehigiamusoe, K.U., Lean, H.H., Smyth, R. (2020), The moderating role of energy consumption in the carbon emissions-income nexus in middle-income countries. Applied Energy, 261, 114215.

Elbahnasawy, N.G. (2021), Can e-government limit the scope of the informal economy? World Development, 139, 105341.

Elgin, C., Kose, M.A., Ohnsorge, F., Yu, S. (2021), Understanding Informality. CEPR Discussion Paper 16497.

Elgin, C., Oztunali, O. (2014), Pollution and informal economy. Economic Systems, 38(3), 333-349.

Erumban, A.A. (2024), Informality and aggregate labor productivity growth: Does ICT moderate the relationship? Telecommunications Policy, 48(1), 102681.

Franco, C., Melica, G., Treville, A., Baldi, M.G., Ortega, A., Bertoldi, P., Thiel, C. (2023), Key predictors of greenhouse gas emissions for cities committing to mitigate and adapt to climate change. Cities, 137, 104342.

Friedrich, R.J. (1982), In defense of multiplicative terms in multiple regression equations. American Journal of Political Science, 26, 797-833.

Garcia-Murillo, M., & Velez-Ospina, J. A. (2017), ICTs and the informal economy: mobile and broadband roles. Digital Policy, Regulation and Governance, 19(1), 58-76.

Ghazouani, T., Maktouf, S. (2024), Impact of natural resources, trade openness, and economic growth on $CO_2$ emissions in oil-exporting countries: A panel autoregressive distributed lag analysis. In: Natural Resources Forum. Vol. 48. Oxford, UK: Blackwell Publishing Ltd. p211-231.

Gheraia, Z., Abdelli, H., Hajji, R., Abid, M. (2023), The asymmetric impact of informal economy in the energy-economic growth nexus in Saudi Arabia. WSEAS Transactions on Business and Economics, 20, 454-466.

Harkat, N., Rahmane, A., Bendjemila, I. (2022), The impact of industrial air pollution on the urban environment of setif: Modeling and mapping of total suspended particles. Engineering, Technology and Applied Science Research, 12(6), 9431-9439.

Harriss-White, B. (2010), Work and wellbeing in informal economies: The regulative roles of institutions of identity and the state. World Development, 38(2), 170-183.

Higón, D.A., Gholami, R., Shirazi, F. (2017), ICT and environmental sustainability: A global perspective. Telematics and Informatics, 34(4), 85-95.

Hossain, M.S. (2011), Panel estimation for $CO_2$ emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. Energy Policy, 39(11), 6991-6999.

Huynh, C.M. (2020), Shadow economy and air pollution in developing Asia: What is the role of fiscal policy? Environmental Economics and Policy Studies, 22(3), 357-381.

Islam, M.S., Rahaman, S.H., Rehman, A.U., Khan, I. (2023), ICT's impact on $CO_2$ emissions in GCC region: The relevance of energy use and financial development. Energy Strategy Reviews, 49, 101147.

Jakučionytė-Skodienė, M., Liobikienė, G. (2023), Changes in energy consumption and $CO_2$ emissions in the Lithuanian household sector caused by environmental awareness and climate change policy. Energy Policy, 180, 113687.

Kahouli, B., Hamdi, B., Nafla, A., Chabaane, N. (2022), Investigating the relationship between ICT, green energy, total factor productivity, and ecological footprint: Empirical evidence from Saudi Arabia. Energy Strategy Reviews, 42, 100871.

Khan, F.N., Sana, A., Arif, U. (2020), Information and communication technology (ICT) and environmental sustainability: A panel data analysis. Environmental Science and Pollution Research, 27, 36718-36731.

Kpognon, K.D. (2022), Effect of natural resources on the size of informal economy in sub-Saharan Africa: An empirical investigation. Structural Change and Economic Dynamics, 63, 1-14.

Lee, J.W., Brahmasrene, T. (2014), ICT, $CO_2$ emissions and economic growth: Evidence from a panel of ASEAN. Global Economic Review, 43(2), 93-109.

Li, R., Guo, J., Wang, Q. (2022), Impact of foreign aid on the ecological sustainability of sub-Saharan African countries. Environmental Impact Assessment Review, 95, 106779.

Masca, S.G., Chis, D.M. (2023), Distributional implications of informal economy in the EU countries: Accounting for the spread of tax evasion benefits and cultural characteristics. Socio-Economic Planning Sciences, 87, 101601.

Narayan, P.K. (2005), The saving and investment nexus for China: evidence from cointegration tests. Applied economics, 37(17), 1979-1990.

Narayan, P.K., Smyth, R. (2008), Energy consumption and real GDP in G7 countries: new evidence from panel cointegration with structural breaks. Energy Economics, 30(5), 2331-2341.

Ndoya, H., Okere, D., laure Belomo, M., Atangana, M. (2023), Does ICTs decrease the spread of informal economy in Africa? Telecommunications Policy, 47(2), 102485.

Nguyen, C.P. (2022), Does economic complexity matter for the shadow economy? Economic Analysis and Policy, 73, 210-227.

Niebel, T. (2018), ICT and economic growth–Comparing developing, emerging and developed countries. World development, 104, 197-211.

Pesaran, M.H., Shin, Y., Smith, R.J. (2001), Bounds testing approaches to the analysis of level relationships. Journal of Applied Econometrics, 16(3), 289-326.

Qayyum, U., Sabir, S., Anjum, S. (2021), Urbanization, informal economy, and ecological footprint quality in South Asia. Environmental Science and Pollution Research, 28, 67011-67021.

Saha, S., Beladi, H., Kar, S. (2021), Corruption control, shadow economy and income inequality: Evidence from Asia. Economic Systems, 45(2), 100774.

Sahay, A., Ranjana, R. (2024), Impact of environmental pollution on the health of workers engaged in informal economy: A case study of Patna metropolitan city. In: Urban Dynamics, Environment and Health: An International Perspective. Singapore: Springer Nature Singapore. p391-411.

Salinas, A., Ortiz, C., Changoluisa, J., Muffatto, M. (2023), Testing three views about the determinants of informal economy: New evidence at global level and by country groups using the CS-ARDL approach. Economic Analysis and Policy, 78, 438-455.

Shahbaz, M., Nuta, A.C., Mishra, P., Ayad, H. (2023), The impact of informality and institutional quality on environmental footprint: The case of emerging economies in a comparative approach. Journal of Environmental Management, 348, 119325.

Sirag, A., Matemilola, B.T., Law, S.H., Bany-Ariffin, A.N. (2018), Does environmental Kuznets curve hypothesis exist? Evidence from dynamic panel threshold. Journal of Environmental Economics and Policy, 7(2), 145-165.

Soytas, U., Sari, R., Ewing, B.T. (2007), Energy consumption, income, and carbon emissions in the United States. Ecological Economics, 62(3-4), 482-489.

Stanley, T.D., Doucouliagos, H., Steel, P. (2018), Does ICT generate economic growth? A meta-regression analysis. Journal of Economic Surveys, 32(3), 705-726.

Sultana, N., Rahman, M.M., Khanam, R., Kabir, Z. (2022), Environmental quality and its nexus with informal economy, corruption control, energy use, and socioeconomic aspects: the perspective of emerging economies. Heliyon, 8(6), e09569.

Usman, A., Ozturk, I., Ullah, S., Hassan, A. (2021), Does ICT have symmetric or asymmetric effects on $CO_2$ emissions? Evidence from selected Asian economies. Technology in Society, 67, 101692.

Uyar, A., Nimer, K., Kuzey, C., Shahbaz, M., Schneider, F. (2021), Can e-government initiatives alleviate tax evasion? The moderation effect of ICT. Technological Forecasting and Social Change, 166, 120597.

Wang, Q., Ren, F., Li, R. (2024a), Exploring the impact of geopolitics on the environmental Kuznets curve research. Sustainable Development, 32(3), 1700-1722.

Wang, Q., Zhang, F., Li, R. (2024b), Free trade and carbon emissions revisited: The asymmetric impacts of trade diversification and trade openness. Sustainable Development, 32(1), 876-901.

Wang, S., Zafar, M.W., Vasbieva, D.G., Yurtkuran, S. (2024c), Economic growth, nuclear energy, renewable energy, and environmental quality: Investigating the environmental Kuznets curve and load capacity curve hypothesis. Gondwana Research, 129, 490-504.

Zhang, C., Liu, C. (2015), The impact of ICT industry on $CO_2$ emissions: A regional analysis in China. Renewable and Sustainable Energy Reviews, 44, 12-19.

Zheng, S., Ahmed, D., Xie, Y., Majeed, M.T., Hafeez, M. (2023), Green growth and carbon neutrality targets in China: Do financial integration and ICT matter? Journal of Cleaner Production, 405, 136923.

Zhu, Q., Cordeiro, J., Sarkis, J. (2013), Institutional pressures, dynamic capabilities and environmental management systems: Investigating the ISO 9000-Environmental management system implementation linkage. Journal of Environmental Management, 114, 232-242.