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Informal economy and environmental degradation in developing countries: the conditioning role of institutional quality

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Environmental degradation, particularly through rising carbon dioxide (CO₂) and greenhouse gas (GHG) emissions, is a pressing challenge for developing countries where large informal economies often escape regulatory oversight. This study investigates the impact of the informal economy on environmental degradation, tests for a potential nonlinear (U-shaped) relationship, and examines how this nexus is moderated by institutional quality. Using annual panel data for 120 developing countries over 2002–2020, we apply fixed effects and system GMM estimators with two measures of informal economy including Multiple Indicators Multiple Causes (MIMIC) model and the Dynamic General Equilibrium (DGE) model estimates, and four institutional indicators including control of corruption (COC), rule of law (ROL), regulatory quality (RQ), and government effectiveness (GE). The results reveal that the informal economy significantly intensifies CO₂ and GHG emissions. Furthermore, the squared term of informal economy confirms a U-shaped relationship, suggesting that informality may initially reduce emissions at very low levels but exacerbates them once it surpasses a threshold. Moreover, the results indicate that higher institutional quality, as reflected in better COC, ROL, RQ, and GE, mitigates the adverse effects of the informal economy on CO₂ and GHG emissions. This highlights a significant substitutability between the informal economy and institutional quality, indicating that improvements in institutions will not only reduce the informality but also weaken its harmful impact on environmental degradation. The findings suggest that policymakers should prioritize strengthening institutional frameworks, particularly in areas related to COC, ROL, RQ, and GE to mitigate the environmental harm caused by the informal economy. Effective institutional reforms can serve as a dual strategy to both formalize economic activities and improve environmental sustainability. Beyond generic governance reforms,

subsidizing cleaner technologies for highly polluting informal sectors (such as brick kilns and leather tanning) and adopting incentive-based formalization programs can effectively curb emissions while safeguarding livelihoods.

KEYWORDS

environmental degradation, GHG emission, CO₂ emissions, informal economy, institutional quality, developing countries

1 Introduction

Environmental degradation has broad and multifaceted consequences that destabilize both human and ecological wellbeing. Air and water pollution contribute to a rise in respiratory and cardiovascular diseases, cancer, and waterborne illnesses (Bala et al., 2021). Furthermore, rising greenhouse gas (GHG) emissions accelerate climate change, leading to more frequent and intense natural disasters, sea-level rise, and desertification. These environmental stresses strain public health systems, reduce labor productivity, and exacerbate social inequalities. Collectively, they pose a serious threat to sustainable development, economic growth, and long-term stability, particularly in countries with weak institutional capacity to manage environmental risks (Wang et al., 2024). In recent times, environmental degradation has been a challenging issue globally, especially in the developing world. The combustion of fossil fuels, industrial emissions, and inadequate waste management practices release harmful pollutants into the atmosphere (Ahmad and Hussain, 2024; Dong et al., 2024). These pollutants not only cause air pollution but also have severe health implications. They contribute significantly to respiratory diseases like asthma, bronchitis, and cardiovascular problems. The population, including the elderly, children, and those with weak health conditions, is especially at risk (Bala et al., 2021).

The level of air pollution in many parts of the world remains dangerously high; 9 out of 10 people breathe in polluted air around the world, and seven million deaths are reported worldwide each year from air pollution, of which two-thirds occurred in Asia (WHO, 2018). These deaths cost approximately \$4.6 trillion annually, equivalent to 6.2% of the global economic output (Fuller et al., 2022). Environmental degradation in the developing world is the consequence of poor environmental measures and ineffective environmental policies, which lead to the transfer of dirty industries there, and these countries usually underrate the environmental aspects to attract multinational corporations, which cause a much larger pollutant atmosphere (Chaudhuri and Mukhopadhyay, 2006; Demiral et al., 2021). Many countries are taking important environmental protection steps that have been effective for developed countries. However, a polluting, unregulated informal economy is a significant issue for developing countries that regulate environmental principles. Therefore, several studies have been found that the large size of the informal sector is an important contributor to environmental degradation in the developing world (Ahmad and Hussain, 2024; Wang et al., 2024). Most of the developing nations face the problem of severe haze pollution. The reason behind haze pollution is the rise and absorption of GHG in the atmosphere, like carbon dioxide (CO₂), which are usually released from unofficial agricultural and industrial activities, which are primarily done in the informal sector and burn fossil fuels

for electricity, heat, and transportation purposes (Abid, 2015; Caporale et al., 2021). The informal sector economy may comprise small-scale manufacturing or industrial undertakings, including small-scale industries, improvised industries such as backyard industries, and units for artisanal production that may employ obsolete technology, substandard equipment, or substandard fuel, and all these contribute to environmental degradation (Shao et al., 2021).

According to estimates from the International Labour Organization, over 2 billion people (61% of the world's employed) work in the informal economy, with 93% of such jobs in emerging and developing countries. Excluding agriculture, half of all workers are informally employed; 85.8% in Africa, 68.2% in Asia-Pacific, 68.6% in Arab States, 40% in the Americas, and 25.1% in Europe and Central Asia (<https://www.ilo.org/resource/news/more-60-cent-world%E2%80%99s-employed-population-are-informal-economy>). Moreover, on average, the informal economy represents about 38.6% of official GDP across 120 selected developing countries. In the developing world, a significant portion of the informal sector involves resource extraction, manufacturing, fabric bleaching and dyeing, craft mining, automobile repair, leather tanning, brick production, metal processing, and retailing. Most of these practices cause environmental degradation (Baksi and Bose, 2010; Engidaw et al., 2024). Furthermore, brick kilns in the traditional way are primarily operated in the informal sector, which is a leading cause of environmental degradation in developing countries. These brick kilns are fueled with several cheap and highly environmentally harmful materials, such as used motor oil, tires, and feces (Blackman, 2000). Moreover, informal sector units usually manufacture intermediary products for formal sector firms on a subcontracting basis (Papola, 1980); for example, the leather-tanning and dyeing process is mainly conducted in the informal sector economy for the garment industry. During this process, bleaching, dyeing, and burning waste produce hazardous chemicals that pollute groundwater and rivers (Baksi and Bose, 2010). In short, the informal economy covers all the production stages that cause environmental degradation.

Figure 1 illustrates the trends of the informal economy (MIMIC estimates) and CO₂ emissions over time. The data indicate a clear trend: as the informal economy grows, CO₂ emissions also increase in selected developing countries. This positive connection shows that informal economic activities, which characteristically lack strict regulatory oversight, significantly contribute to environmental degradation.

The low quality of institutions causes the growth of the informal economy. Corrupt bureaucratic and public administration systems, tied with weak law enforcement, often lead to the growth of the informal sector. Conversely, a strong rule of law (ROL), effective control of corruption (COC), better regularity quality (RQ), and more government effectiveness (GE) can decrease the size of the

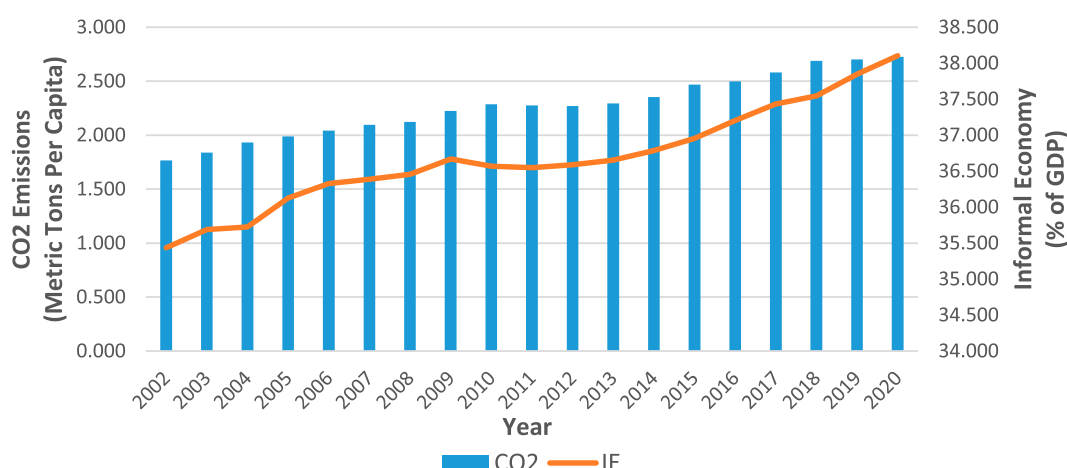


FIGURE 1

Average size of the informal economy (MIMIC estimates) and CO₂ emissions in 120 developing economies. Source: Author's construction based on Informal Economy Database (World Bank) and World Development Indicators (World Bank).

informal economy, making it more beneficial for businesses to operate formally (Feld and Schneider, 2010). Strong institutions also strengthen investor confidence, ensure fairness, and promote the fair distribution of resources (Destek et al., 2023). This reduces the occurrence of informal economic activities, which helps lower environmental degradation (Biswas et al., 2012; Huynh, 2020). However, rigorous environmental regulations, like higher pollution taxes, might involuntarily push production and emissions into the informal economy (Chaudhuri and Mukhopadhyay, 2006). Weak institutions, marked by poor enforcement of environmental laws, can increase the number of firms operating informally and reduce pollution (Baksi and Bose, 2010). Additionally, institutional weaknesses may cause firms to outsource production to the informal sector to avoid pollution control costs, harming environmental quality.

In short, the informal economy can harm environmental quality if actions are not taken. Thus, any empirical analysis or policy recommendation on environmental issues that ignores the presence of the informal sector and the role of institutions would be incomplete. Therefore, the main objective of this study is to investigate the impact of the informal economy on environmental degradation, test for a potential nonlinear (U-shaped) relationship, and examine how this nexus is moderated by institutional quality. Despite the critical role the informal sector plays in the livelihoods of millions in developing countries, its environmental consequences remain underexplored in the academic literature, particularly when considering the nonlinear relationship and moderating influence of institutional quality. Existing research has predominantly focused either on the direct environmental impacts of informality (Abid, 2015; Canh et al., 2019; Pang et al., 2021; Ahmad and Hussain, 2024) or on the role of institutional quality in economic formalization, but few studies have examined how institutional factors condition the informal economy and environmental degradation nexus (Dada and Ajide, 2021; Dada et al., 2022; Wang et al., 2024). Furthermore, the possibility of a nonlinear (U-shaped) relationship where the environmental impact of informality initially declines but rises again once informality

exceeds a certain threshold has not been systematically investigated in a cross-country developing-country context. Moreover, prior analyses often rely on limited datasets, narrow geographic scopes, or singular measures of informality and pollution emissions, thereby constraining the robustness and applicability of their conclusions.

This study fills these crucial gaps by leveraging a large-scale, cross-country panel dataset encompassing 120 developing countries over an extended period (2002–2020), as the informal economy is a pervasive concern affecting all developing countries (Ahmad and Hussain, 2023). Furthermore, we employ multiple rigorous proxies to ensure robustness. For the informal economy, we use estimates from both the Multiple Indicators Multiple Causes (MIMIC) model and the Dynamic General Equilibrium (DGE) model. For environmental degradation, we rely on indicators of CO₂ emissions and GHG emissions. Additionally, the inclusion of key institutional quality indicators such as COC, ROL, RQ, and GE provides a nuanced understanding of how governance structures can mitigate or exacerbate environmental harm linked to informal activities. This multidimensional approach not only advances theoretical understanding but also provides actionable insights for policymakers, highlighting that strengthening institutional frameworks is indispensable for simultaneously reducing the size of the informal sector and curbing its detrimental environmental effects. By linking informality, institutional quality, and environmental degradation, the study contributes to advancing theoretical understanding and provides actionable insights for policymakers. It demonstrates that stronger institutions not only reduce the size of the informal economy but also weaken its harmful ecological effects, including potential nonlinear dynamics. These findings align with the Sustainable Development Goals, particularly SDG 8 (Decent Work and Economic Growth), SDG 13 (Climate Action), and SDG 16 (Peace, Justice and Strong Institutions). Ultimately, the study underscores that sustainable development in the developing world requires integrated strategies, as economic informality, governance, and environmental quality are deeply interconnected. Strengthening institutional frameworks can thus foster both greener and more inclusive economies.

The research is structured as follows: [Section 2](#) offers an in-depth literature review, highlighting key findings and theoretical underpinnings from previous research. [Section 3](#) reveals the data sources and outlines the methodological approach employed in the research. [Section 4](#) presents the results and discusses the findings in detail. [Section 5](#) summarizes the conclusions and provides policy implications.

2 Theoretical and empirical review of the literature

2.1 Informal economy and environmental degradation

Numerous studies have highlighted the causes of pollution emissions. In this context, [Blackman \(2000\)](#) inspected the informal brick industry of Mexico and found that the brick industry utilized propane gas, a pollution source. From his point of view, the developing countries' informal economies usually comprise unlicensed and low-tech small businesses, which lead to environmental degradation and pose a challenge to environmental authorities. To further extend the research, [Blackman et al. \(2006\)](#) studied the informal sector in Mexico and revealed that undocumented activities constitute a significant source of pollution emissions because, in these activities, firms use low technology, and these activities operate outside of formal regulatory frameworks. This means no environmental regulations or standards are often imposed on these activities. As a result, informal enterprises may not have to comply with pollution control measures, leading to increased emissions and pollution. Moreover, [Baksi and Bose \(2010\)](#) claimed that the intensive environmental rules induce the official economy to shift its production activities into the informal economy; hence, this act causes environmental degradation.

By developing a theoretical model, [Biswas et al. \(2012\)](#) combine pollution, corruption, and the informal economy into an integrated framework to expose how the informal economy increases pollution emissions under a specific rank of bribery. The study suggested that if government officials-controlled corruption, they could effectively minimize the impact of the informality on pollution. [Abid \(2015\)](#) analyzed the co-integration between the unofficial economic sector and CO₂ emissions from a related perspective, finding a positive effect. [Chen et al. \(2018\)](#) examined this relationship across 30 Chinese provinces, increasing the sample size and contributing further to the literature by backing the hypothesis of a positive affiliation of the informal economy with CO₂ emissions. To broaden the scope, [Canh et al. \(2019\)](#) conducted a comprehensive analysis across 106 economies globally, estimating the impact of the informal economy on various pollutants such as CH₄, CO₂, and N₂O emissions. They revealed that the informality increases the levels of N₂O, CH₄, and other pollutants; however, the relationship with CO₂ emissions was insignificant. Additionally, [Ozgun et al. \(2021\)](#), through a cross-sectional study of 160 nations, found that the illegal sector significantly raises pollution emissions. Furthermore, [Nkengfack et al. \(2021\)](#) investigated the impact of informality on pollution emissions in Africa. Their findings signified a negative correlation between informality and pollution emissions,

suggesting that larger informal activities may reduce emissions. However, this effect was only observed in lower-income countries. Overall, the results suggest that informality does not necessarily cause environmental harm in Africa.

The previous studies have also pointed out the non-monotonic connection between informality and pollution emissions. In this regard, [Elgin and Oztunali \(2014\)](#) explored the connection between informality and CO₂ emissions using panel data of 152 economies and established a U-shaped association. In the same vein, [Zhou \(2019\)](#) observed that there is an optimal income level through which CO₂ emissions can be minimized in the presence of informality. In the same manner, [Wang et al. \(2019\)](#) indicated that the interaction of the informal economy and corruption intensifies the pollution emissions in the case of China. Likewise, [Huynh \(2020\)](#) empirically examined the interaction between the informal economy, CO₂ emissions, and fiscal policy in the context of Asian developing economies. In addition, the influence of taxation and government expenditure on CO₂ emissions was tested. The results found that the size of the informal economy positively affects CO₂ emissions. As a result, expansionary fiscal policy reduces the informal economy, which leads to reduced CO₂ emissions. However, a higher government budget was concerned with lessening the impact of informality, while a higher tax burden was associated with an increased rate of informality. Moreover, [Pang et al. \(2021\)](#) also reported that the informal economy and pollution emissions have U-shaped non-linear relationships: the size pattern of both, the informal economy and pollution emissions, rises according to the growth in the extent of the environmental regulations, but after the threshold level, both fall. In the most recent study, [Ahmad and Hussain \(2024\)](#) and [Wang et al. \(2024\)](#) found that the informal economy significantly increases CO₂ emissions in developing countries.

2.2 Institutional quality and environmental degradation

The sustainability of the environment is vital, and institutions play an important part in achieving it. In this context, [Usman et al. \(2022\)](#) estimated the impact of COC and *per capita* income on environmental quality in Africa. The study revealed that COC and high *per capita* income increase CO₂ emissions; however, the interaction between COC and income level decreases the CO₂ emissions. It is noticed that at higher income levels, the effect of COC on CO₂ emissions is minimized. Furthermore, [Zhang et al. \(2022\)](#) investigated the impact of institutional quality on CO₂ emissions in the BRICS economies. The study found that institutional quality indicators, including COC, ROL, and government stability, have a long-term inverse effect on CO₂ emissions. Based on the findings, the study suggested that effective institutions are advantageous in reducing pollution in the BRICS economies.

Furthermore, [Khan et al. \(2022\)](#) pointed out that strong institutions, as shown by regulatory quality, ROL, political stability, and COC, help reduce pollution in developing countries. [Cole \(2007\)](#) carried out a cross-sectional study on 94 countries and found that corruption led to a decrease in environmental regulations, causing more harm to the environment. [Karim et al. \(2022\)](#) studied 30 African countries to find out how six aspects of

institutions influence pollution emissions. The analysis suggested that stronger regulations, better ROL, and higher COC lead to a decline in pollution emissions. [Sultana et al. \(2022\)](#) looked at how institutional quality, particularly COC, affects CO₂ emissions in developing countries and showed that better management of corruption is linked to a decrease in CO₂ emissions. The researchers [Hwang et al. \(2024\)](#) studied how corruption influences pollution emissions, mainly focusing on CO₂ emissions in the Commonwealth States. It is shown that corruption leads to more CO₂ emissions and, at the same time, indirectly decreases CO₂ emissions because of environmental policies.

Similarly, [Lapatinas et al. \(2019\)](#) have claimed that in contexts where corruption prevails, politicians may invest large shares of public money in environmental programs in order to extract payment, not to enhance environmental quality. Furthermore, [Chen et al. \(2018\)](#) confirmed that an increase in corrupt officers may weaken the environmental laws, thus leading to a constant increase in emissions from the illegal production of pollutants. [Sinha et al. \(2019\)](#) also revealed that corruption hinders or compromises the execution of environmental policies, and hence, there is an increase in the discharge of pollutants. [Biswas et al. \(2012\)](#) have proposed an integrated framework where pollution emissions, corruption, and informal economy are integrated and showed how corruption enables the growth of pollution to a certain extent; they have also postulated that checks on corruption will help reduce the impact of informal economy on pollution emissions. Similarly, [Ivanova \(2011\)](#) studied 39 European countries and found that polluting enterprises pay bribes to government officials to avoid reporting their pollutant release, avoid pollution taxes, and contribute to pollution emissions.

Furthermore, [Liu et al. \(2021\)](#) found that corruption and poor governance of ROL lead to enhanced environmental degradation. Most recently, [Ofoeda et al. \(2024\)](#) examined the connection between institutional quality and CO₂ emissions across 138 countries. The study recognized a critical threshold of institutional quality required for green technology to reduce carbon emissions effectively. The results indicate that institutions' performance plays a key role in influencing the impact of green technology on carbon emissions, particularly when it exceeds a specific threshold. The study recommends that countries focus on fostering political stability, creating robust legal and regulatory frameworks, corruption control, and improving government efficiency to support green technology investments and achieve more favorable environmental outcomes.

2.3 Institutional quality and informal economy

Many studies in the literature, both empirical and theoretical, explore the relationship between institutional indicators and informality. In this regard, [Khan and Rehman \(2022\)](#) note that weak institutions foster the growth of the informal economy while strong institutions help to move enterprises from the unofficial sector to the formal financial system. Moreover, [Butt et al. \(2024\)](#) further supported the evidence that a higher level of institutional performance influences pollution emissions. Based on their findings,

they concluded that better institutional quality can promote ecological changes, thereby improving the quality of the environment. Hence, there is a need to have strong institutions to pass legislation that can help address the threats to the global environment. Similarly, [Khattak et al. \(2024\)](#) analyzed the informal economy, institutional quality, and banking competition for 127 countries. Their results indicate that higher banking competition and more robust institutions generally reduce the informal economy. Furthermore, the effect of competition on the informal economy is higher in countries with lower performance of institutions; at the same time, the significance of institutional quality is higher in environments with lower levels of competition. In addition, [Dang et al. \(2023\)](#) examined 29 Asian countries and found that higher quality in institutions is linked to a smaller informal economy. [Lacobuta et al. \(2014\)](#) also studied the causes of informal economy in European Union countries, finding that those with high ROL, strong regulations, and greater labor freedom have less informal economic activity. They found that better institutions are important for reducing the level of informality. In their view, [Dada et al. \(2021\)](#) notice that the informal sector is more prominent in areas where institutions are not very strong. In addition, [Huynh \(2020\)](#) presented evidence that reinforcing the ROL and COC can help reduce informality, supporting the Legalist view that institutions help shape actions in the informal sector.

In this context, [Dreher et al. \(2009\)](#) conducted a panel study of 145 economies and found that corruption and informality are positively linked. Their study also showed that a higher institutional quality significantly reduces the informal economy. Likewise, [Johnson et al. \(1997\)](#), in their study of Latin America, OECD, and transition economies, revealed a direct relationship between weak ROL, corruption, and the informal economy in these countries. In the most recent study, [Barra and Papaccio \(2024\)](#) pointed out that countries with good institutions, such as Italy, have lower informal economic growth, thus enforcing the growth of formal employment and fighting corruption. Further, [Mveng and Henri \(2024\)](#) did a comparative analysis of how historical factors affect the informal economy through the prism of corruption control. They established that states with high levels of corruption control have a low informal economy size.

There are several theories that link institutional quality to the persistence and expansion of the informal economy. One of the most influential is the Legalist theory, also referred to as the Neo-liberal theory. This perspective, pioneered by [De Soto \(1989\)](#), [De Soto \(2000\)](#), emphasized how individuals and entrepreneurs react to excessive government regulation and bureaucratic inefficiencies. According to this view, many actors deliberately choose informal operations to avoid the burdens of the formal system, such as lengthy registration procedures, high tax rates, and mandatory social security contributions. By remaining outside the formal framework, they aim to escape unnecessary costs and delays, while also retaining greater flexibility in managing their resources. The Legalist approach advocates for reducing or eliminating institutional constraints that stifle entrepreneurship, arguing that excessive state intervention undermines the market's ability to allocate resources efficiently ([Williams, 2014](#)). It also highlights how weak institutional quality, manifested through corruption, complex legal requirements, and administrative delays, further pushes individuals toward informal economic

activities. In such environments, entrepreneurs often create their own informal rules and systems of governance, effectively substituting for the absent or ineffective formal institutions (Chen, 2012). From this standpoint, the informal economy is not merely a survival strategy but also a rational response to institutional failures. De Soto (2000) suggested that informality can accumulate wealth and, in certain contexts, even challenge or displace formal economic structures. Similarly, Cross and Johnson (2000) argued that the informal sector expands most rapidly where the formal economy falters, absorbing large segments of unemployed labor and mitigating the social impacts of economic downturns. Thus, the size and dynamics of the informal economy are deeply interwoven with the quality of institutions, with weak governance and rigid legal frameworks acting as catalysts for its growth.

2.4 Literature gap and hypothesis development

Despite growing attention to the environmental consequences of the informal economy and the role of institutions, some critical gaps remain. First, most studies analyze these factors separately, overlooking how institutional quality may condition the informality-environment relationship. Second, while some evidence suggests that the impact of informality on emissions is not linear, the possibility of a U-shaped relationship has not been systematically tested in a cross-country developing world context. Finally, much of the existing research relies on narrow datasets or single proxies, limiting the robustness of conclusions. This study addresses these gaps by (i) jointly examining the direct and interactive effects of informality and institutional quality, (ii) testing for potential nonlinear (U-shaped) dynamics between informality and emissions, and (iii) employing multiple measures of both informality and institutions across 120 developing countries over 2002–2020. Based on these gaps, the following hypotheses are proposed:

H1: The informal economy significantly increases environmental degradation in developing countries.

H2: Stronger institutional quality moderates the adverse effect of the informal economy on environmental degradation, reducing its environmental harm.

H3: The relationship between the informal economy and environmental degradation follows a U-shaped pattern, with environmental harm intensifying beyond a certain threshold of informality.

3 Data and methodology

3.1 Data and variables

We utilized a balanced panel dataset of 120 selected developing countries from 2002 to 2020 to empirically test the models. The analysis begins in 2002, as this is the earliest year for which the continuous data of institutional quality are available, and also, this

period marks the global push for governance reforms and institutional strengthening under international development agendas, making it highly relevant for our analysis. The study period ended in 2020 due to limitations in data availability, mainly concerning the informal economy. This study focuses on developing countries around the world as a case study. The developing countries are chosen because they offer a valuable context for studying the above-mentioned issues, given their challenging characteristics. These characteristics include the large size of the informal economy, high levels of environmental degradation, and underdeveloped institutions. Studying these countries allows us to capture dynamics that are less visible in developed economies, where informality is comparatively smaller and institutions are more established. Thus, both the temporal scope and country selection reflect not only data availability but also theoretical and policy relevance, addressing the structural conditions where the informal economy is most pervasive.

Environmental Degradation acts as a dependent variable in the models and is measured by CO₂ and GHG emissions. The factors in CO₂ emissions are primarily related to human activities that release CO₂ into the atmosphere. These factors encompass burning oil, coal, and natural gas for activities such as transportation, generating electricity, and industrial operations. The cement manufacturing process involves releasing CO₂ as a byproduct, known as process emissions. Various industrial activities, such as chemical production, metal smelting, and the use of solvents, can result in the release of carbon emissions. CO₂ is released when fossil fuels are burned for heating, cooking, and powering appliances in homes and businesses (Xu and Lin, 2015). Moreover, GHG emissions encompass a broader array of pollutants, including CO₂, CH₄, N₂O, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, emitted from sectors such as energy, industry, agriculture, waste management, and land use change.

Informal Economy is our key explanatory variable, defined as the production of goods and services that occurs outside the formal regulatory and institutional framework. Its existence is typically driven by monetary incentives (e.g., tax evasion), regulatory avoidance (e.g., circumventing labor or business regulations), and institutional failures (e.g., corruption or weak legal enforcement) (Elgin et al., 2021). We use two estimates of the informal economy, including the MIMIC and DGE model approaches. The MIMIC model estimates the informal economy as a latent variable, linking structural causes (e.g., taxation, regulation, corruption) with observable indicators such as currency demand and labor market gaps. In contrast, the DGE model uses a macroeconomic simulation, where households and firms allocate resources between formal and informal sectors, making informality an equilibrium outcome of agent decisions.

Institutional Quality acts as a moderating variable in our models. We capture the institutional quality using the four indicators, including COC, ROL, RQ, and GE. The concept of COC refers to people's perception regarding the extent to which those in public office use their power for personal gain. This encompasses all types of corruption, from small acts to large-scale cases, and the extent to which the privileged classes and private interests influence government issues. The ROL involves how people are confident in and follow the rules of society. It reflects the extent to which it is worthwhile to implement contracts, secure property rights,

TABLE 1 Variables, definitions, and data sources.

Variables	Definitions	Expected signs	Sources
Environmental degradation			
Carbon Dioxide Emissions (CO ₂)	CO ₂ emissions (metric tons <i>per capita</i>)		WDI, WB
Total Greenhouse Gas Emissions (GHG)	Total greenhouse gas emissions (metric tons of CO ₂ equivalent)		WDI, WB
Informal Economy			
Informal Economy (I.E.,_MIMIC)	Size of the informal economy, estimates of the MIMIC approach (% of GDP)	+	IED, WB
Informal Economy (I.E.,_DGE)	Size of the informal economy, estimates of DGE approach (% of GDP)	+	IED, WB
Institutional Quality			
Control of Corruption (COC)	Control of corruption index: −2.5 to 2.5 (higher score indicates a higher COC)	−	WGI, WB
Rule of Law (ROL)	Rule of law index: −2.5 to 2.5 (higher score indicates a stronger rule of law)	−	WGI, WB
Regularity Quality (RQ)	Regularity quality index: −2.5 to 2.5 (higher score indicates a higher RQ)	−	WGI, WB
Government Effectiveness (GE)	Government effectiveness index: −2.5 to 2.5 (higher score indicates a more GE)	−	WGI, WB
Control Variables			
GDP Growth (GDPG)	Growth of GDP (annual%)	+	WDI, WB
FDI Inflow (FDI)	Foreign direct investment, net inflows (% of GDP)	+	WDI, WB
Renewable Energy Consumption (REC)	Renewable energy consumption (as % of the total final energy consumption)	−	WDI, WB
Population Growth (POPG)	Population growth (annual %)	+	WDI, WB

WDI, denotes World Development Indicators; IED, denotes the informal economy database; WGI, denotes World Governance Indicators, and WB, denotes World Bank.

guarantee effective police services, and provide reliable and fair judicial systems. It also reflects how prevalent crime and violence are within a society. However, the RQ reflects perceptions regarding the capability of the government to design and establish healthy policies and regulations that would allow and encourage the development of the private sector. Moreover, the GE reflects the image of the quality of the public services, the quality of the civil service and the extent to which it is not tied to the political forces, the quality of the policy making and execution, and the image of whether the government is committed to such policies.

Control Variables are selected based on prior relevant literature (Ohlan, 2015; Zmami and Ben-Salha, 2020; Shaari et al., 2021; Huang et al., 2022). We employ GDP growth, FDI, renewable energy consumption, and population growth as control variables. The details of the variables are presented in Table 1.

3.2 Model specifications

To empirically test the proposed hypotheses, we follow the methodological frameworks of Canh et al. (2019), Dada et al. (2021), Dada and Ajide (2021), Ahmad and Hussain (2024), and Wang et al. (2024). Our empirical strategy proceeds in two steps. First, we estimate the direct effect of the informal economy, as measured by MIMIC and DGE model estimates, on environmental degradation, as proxied by CO₂ and GHG emissions. Second, we assess the nonlinear nature of the informal economy and the moderating role of institutional quality (IQ), which is proxied by the control of corruption (COC), rule of law (ROL), regulatory

quality (RQ), and government effectiveness (GE). The baseline dynamic panel model is specified as:

$$ED_{it} = \alpha_0 + \alpha_1 ED_{it-1} + \alpha_2 IE_{it} + \alpha' X_{it} + v_i + \omega_t + \mu_{it} \quad (1)$$

Equation 1 represents the linear model, where ED denotes environmental degradation, proxied by CO₂ and GHG emissions. I.E., represents the informal economy, measured by MIMIC and DGE model estimates. X is a vector of control variables. v_i and ω_t capture country and time-fixed effects, respectively; and μ_{it} is the error term. To examine the nonlinear impact of I.E., and the moderating role of IQ, we include the squared term of I.E., and interaction terms between I.E., and IQ, respectively. The extended model is presented as:

$$ED_{it} = \beta_0 + \beta_1 ED_{it-1} + \beta_2 IE_{it} + \beta_3 IE_{it}^2 + \beta_4 (IE_{it} \times IQ_{it}) + \alpha' X_{it} + v_i + \omega_t + \mu_{it} \quad (2)$$

where I.E.,² represents the square of the informal economy. IQ represents the institutional quality, which is proxied by COC, ROL, RQ, and GE. I.E., × IQ denotes the interaction between I.E., and IQ. To explore the conditional effect of I.E., on ED, under various levels of IQ, we take the partial derivatives of Equation 2 with respect to I.E.,

$$\frac{\partial (ED_{it})}{\partial (IE_{it})} = \beta_2 + 2\beta_3 IE_{it} + \beta_4 IQ_{it} \quad (3)$$

The signs of β_2 and β_4 from Equation 3, indicate whether IQ moderates the environmental impact of, I.E., in a complementary or substitutive manner. If both coefficients share the same sign, a

complementarity effect is inferred; otherwise, the relationship is substitutive.

3.3 Estimation method

This study employs both fixed effects (FE) and system generalized method of moments (system GMM) estimators. Using a combination of estimation techniques allows for robust inference and strengthens the empirical validity of the findings. Initially, both FE and random effects (RE) models are considered. To choose the appropriate specification, we perform the Hausman test, which compares the consistency and efficiency of RE and FE estimators. A rejection of the null hypothesis (that regressors are uncorrelated with country-specific effects) supports the use of FE (Hausman and Taylor, 1981).

We begin with the FE estimator, which controls for time-invariant, unobserved heterogeneity across countries, such as geographic, cultural, or historical institutional differences that might otherwise bias the estimates (Fernández-Val and Weidner, 2018). By including country and time fixed effects, the model accounts for shocks that are common across all countries in a given year, such as global economic crises or international environmental agreements (Bai, 2009). However, the FE model rests on the assumption of strict exogeneity. Several key explanatory variables, particularly the informal economy and institutional quality indicators, are likely to be endogenous. For example, prior studies show a bidirectional relationship between the informal economy and CO₂ emissions, indicating the possibility of reverse causality (Dada et al., 2022; Dongmo et al., 2023). Additionally, omitted variable bias and measurement errors, especially prevalent in estimates of the informal sector and institutional performance, may further compromise the validity of the FE results (Wooldridge, 2010). To address these econometric concerns, we also apply the system GMM estimator developed by Arellano and Bond (1991) and extended by Blundell and Bond (1998). System GMM is particularly suitable for dynamic panel data with a relatively large cross-sectional dimension and a smaller time dimension, as in our dataset of 120 developing countries over the period 2002–2020. This method is capable of correcting for simultaneity bias, dynamic endogeneity, and unobserved heterogeneity. It does so by estimating a system of equations in both first differences and levels, using lagged values of the endogenous variables as instruments (Roodman, 2009). The inclusion of lagged dependent variables, such as past CO₂ emissions, is also crucial given the persistence of environmental degradation over time (Canh et al., 2019; Dada et al., 2021; Ahmad and Hussain, 2024).

There is a strong theoretical justification for employing an estimator that controls for endogeneity. Informal sector activities in many developing countries, including small-scale mining, metalworking, brick making, leather tanning, and vehicle repair, are typically unregulated and contribute substantially to environmental degradation (Baksi and Bose, 2010). On the other hand, stringent environmental policies and higher operational costs in the formal economy may encourage firms and individuals to shift to the informal sector to reduce compliance costs, thereby creating a feedback loop between informality and emissions (Dongmo et al.,

2023). Neglecting such interdependence can result in biased and inconsistent parameter estimates, particularly when relying solely on static models such as OLS or FE (Ullah et al., 2018). System GMM offers a robust framework for isolating causal relationships under these conditions. Diagnostic checks, including the Arellano-Bond test for autocorrelation, the Hansen and Sargan tests for over-identifying restrictions, are applied to assess the validity of the instruments and the overall reliability of the model. The estimation strategy begins with FE and proceeds to system GMM to mitigate endogeneity concerns. One limitation of FE and system GMM is that they are not fully robust to cross-sectional dependence (CSD) and slope heterogeneity, which may arise because developing countries often share regional shocks (e.g., global fuel price fluctuations, climate agreements) and may differ in how institutions shape the informality–environment nexus. In this study, we partially address these concerns by incorporating both country and time fixed effects, which absorb unobserved heterogeneity and common global shocks, and by employing robust standard errors clustered at the country level to reduce the influence of residual cross-sectional correlation. The FE and system GMM approaches remain appropriate for our research objectives given the dynamic, endogeneity-prone nature of the data. Robust standard errors were utilized in all estimations through the “robust” option in Stata. This approach enhances the reliability of the results by producing standard errors that are more consistent with the underlying data structure. For dynamic panel estimation, we used the “xtabond2” procedure in Stata, which is specifically designed to handle datasets with potential endogeneity, dynamic relationships, and unobserved heterogeneity. The estimation flowchart is also present in Figure 2.

4 Results and discussions

4.1 Descriptive statistics

Table 2 describes the summary statistics for the study variables across 2280 observations used in the models. The average CO₂ emissions are 2.12, with a standard deviation of 2.60, while the average GHG emissions are 7.4E-07, with a standard deviation of 2.2E-05, demonstrating considerable variability in emissions levels. The, I.E.,_MIMIC has a mean value of 38.06, ranging from 11.58 to 68.21, and a standard deviation of 10.03, reflecting substantial differences across observations. The, I.E.,_DGE has a mean value of 36.43, ranging from 8.02 to 66.45, and a standard deviation of 10.04. The mean values of COC, ROL, RQ, and GE are −0.58, −0.59, −0.48, and −0.53, respectively, with moderate variability reflected in their standard deviations of 0.55, 0.56, 0.62, and 0.59. These statistics offer a foundational understanding of the data's characteristics, highlighting the variability and range of the key variables.

4.2 Correlation matrix and Variance Inflation Factor

Table 3 shows important relationships between the variables through the correlation matrix. CO₂ emissions are strongly linked with, I.E.,_MIMIC (0.62) and, I.E.,_DGE (0.47), indicating that a

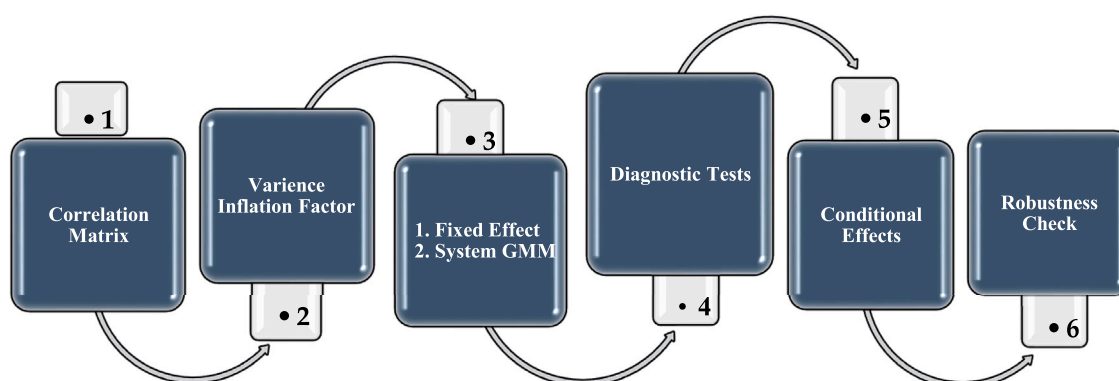


FIGURE 2
Estimation flowchart. Source: Author's own construction.

TABLE 2 Summary of the variables.

Variables	Observations	Mean	Std. Dev	Min	Max
CO ₂	2,280	2.12	2.60	0.02	15.34
GHG	2,280	7.4E-07	2.2E-05	-1.9E-04	5.4E-05
I.E.,_MIMIC	2,280	38.06	10.03	11.58	68.21
I.E.,_DGE	2,280	36.43	10.04	8.02	66.45
COC	2,280	-0.58	0.55	-1.69	1.66
ROL	2,280	-0.59	0.56	-1.87	1.26
RQ	2,280	-0.48	0.62	-1.75	1.52
GE	2,280	-0.53	0.59	-1.68	1.45
GDPG	2,280	4.03	5.78	-50.34	86.83
FDI	2,280	4.01	6.39	-37.17	103.34
REC	2,280	42.66	31.09	0.02	98.27
POPG	2,280	1.75	1.31	-5.32	12.01

larger informality may lead to greater environmental damage (Dada et al., 2022; Wang et al., 2024). The same pattern is seen with GHG emissions, which also have positive correlations with, I.E.,_MIMIC (0.44) and, I.E.,_DGE (0.41). However, COC, ROL, RQ, and GE are negatively correlated with CO₂ (by -0.39, -0.31, -0.35, and -0.29) and GHG (by -0.33, -0.35, -0.39, and -0.45), revealing that countries with stronger institutional quality have lower levels of environmental damage (Wang et al., 2024). In addition, the COC, ROL, RQ, and GE show a negative correlation with the informal economy measures, ranging from -0.28 to -0.62, indicating that better institutions tend to lower the informality (Dongmo et al., 2023; Ahmad and Hussain, 2024).

To check for possible multicollinearity among explanatory variables, we analyzed the Variance Inflation Factor (VIF). All the variables have VIF values well below the standard threshold of 5, which is shown in Table 4. The highest VIF is seen for, I.E.,_MIMIC (3.612), and the lowest is for FDI (1.031), which indicates that multicollinearity is not a major issue in our data. They suggest that the effects of each explanatory variable on the outcome can be

clearly understood in the regression models. Moreover, low VIF values enhance the credibility of the estimated coefficients and their policy implications by ensuring that no variable's effect is masked by collinearity with other regressors (Wooldridge, 2010).

4.3 Regression analysis

The empirical analysis begins with the estimation of the direct effect of the informal economy on environmental degradation, as measured by CO₂ emissions. Four separate model specifications are estimated, two using FE and two using system GMM, each employing one of two alternative measures of informality: the MIMIC-based index and the DGE-based index. The corresponding estimation results and diagnostic tests are presented in Table 5. The Hausman test values support the FE estimations. The diagnostic statistics from the system GMM models indicate that the models are well-specified and the instruments are valid. The AR(1) is significant in both dynamic models, as expected, while the AR(2) is insignificant

TABLE 3 Correlation matrix.

Variables	CO ₂	GHG	I.E.,_MIMIC	I.E.,_DGE	COC	ROL	RQ	GE	GDPG	FDI	REC	POPG
CO ₂	1.000											
GHG	0.55***	1.000										
	(0.001)											
I.E.,_MIMIC	0.62***	0.44***	1.000									
	(0.003)	(0.002)										
I.E.,_DGE	0.47***	0.41***	0.44***	1.000								
	(0.004)	(0.005)	(0.000)									
COC	−0.39**	−0.33**	−0.59***	−0.62***	1.000							
	(0.041)	(0.023)	(0.000)	(0.000)								
ROL	−0.31***	−0.35**	−0.41**	−0.44***	0.59***	1.000						
	(0.003)	(0.038)	(0.015)	(0.000)	(0.001)							
RQ	−0.35***	−0.39**	−0.28*	−0.48**	0.51***	0.41**	1.000					
	(0.008)	(0.023)	(0.072)	(0.015)	(0.000)	(0.027)						
GE	−0.29**	−0.33**	−0.45**	−0.37**	0.48**	0.58***	0.38*	1.000				
	(0.024)	(0.034)	(0.025)	(0.027)	(0.034)	(0.000)	(0.072)					
GDPG	0.35**	0.28**	−0.31**	0.24***	0.38**	0.27***	0.37**	0.43**	1.000			
	(0.032)	(0.041)	(0.024)	(0.013)	(0.031)	(0.000)	(0.041)	(0.024)				
FDI	0.22*	0.19**	0.041*	0.06*	0.18**	0.11**	0.27*	0.29***	0.19***	1.000		
	(0.071)	(0.032)	(0.067)	(0.011)	(0.029)	(0.042)	(0.061)	(0.001)	(0.000)			
REC	−0.65***	−0.44***	0.08*	0.09*	0.12	0.19**	0.21**	0.15*	0.25**	0.30***	1.000	
	(0.001)	(0.004)	(0.081)	(0.063)	(0.281)	(0.040)	(0.024)	(0.081)	(0.031)	(0.000)		
POPG	0.24*	0.12**	0.401***	0.22***	0.08	0.10	0.12	0.23**	0.11***	0.04	0.06*	1.000
	(0.081)	(0.021)	(0.001)	(0.006)	(0.251)	(0.154)	(0.171)	(0.022)	(0.001)	(0.261)	(0.091)	

P-values are in (); *, **, *** indicate significant at 10%, 5%, 1%, respectively.

TABLE 4 Results of the variance inflation factor.

Variables	VIF	1/VIF
I.E.,_MIMIC	3.612	0.277
I.E.,_DGE	2.173	0.460
COC	1.991	0.502
ROL	3.194	0.313
RQ	2.124	0.471
GE	1.985	0.504
GDPG	1.152	0.868
FDI	1.031	0.969
REC	1.261	0.793
POPG	1.091	0.916

(p-values of 0.281 and 0.307), suggesting no serial correlation in the differenced residuals. The Hansen and Sargan tests confirm the validity of the instruments, with p-values exceeding conventional

significance levels, indicating no overidentification problems. The estimation results consistently show that the informal economy is positively and significantly associated with CO₂ emissions, regardless of the estimator or the measure of informality used. In the FE models, the coefficient for the MIMIC-based informality index is 0.149 ($p < 0.01$), while the coefficient for the DGE-based index is 0.109 ($p < 0.05$). These results indicate that a one-unit increase in informality is associated with a 0.149 and 0.109 unit increase in CO₂ emissions, respectively. The results are even more pronounced in the system GMM estimations, where the coefficients rise to 0.171 ($p < 0.05$) for the MIMIC-based index and 0.211 ($p < 0.01$) for the DGE-based index. These findings suggest that after accounting for endogeneity and dynamic persistence in emissions, the effect of informality on environmental degradation becomes stronger.

The positive and statistically significant relationship between the informal economy and CO₂ emissions supports our hypothesis that the informal economy significantly increases the level of environmental degradation in developing countries. This result is theoretically justified. Informal firms often operate outside the purview of environmental regulations, avoid compliance with emission standards, and rely on outdated or inefficient

TABLE 5 Impact of informal economy on CO₂ emissions.

Dep. Var: CO ₂	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
CO ₂ (–1)			0.842***	0.802***
			(0.101)	(0.116)
Informal Economy				
I.E.,_MIMIC	0.149***		0.171**	
	(0.032)		(0.081)	
I.E.,_DGE		0.109**		0.211***
		(0.054)		(0.009)
Control Variables				
GDPG	0.102*	0.098**	0.045**	0.104*
	(0.056)	(0.054)	(0.021)	(0.056)
FDI	0.097**	0.074*	0.178**	0.121*
	(0.041)	(0.042)	(0.089)	(0.070)
REC	–0.084***	–0.066**	–0.056**	–0.110**
	(0.009)	(0.033)	(0.025)	(0.045)
POPG	0.127*	0.085*	–0.035	0.131**
	(0.071)	(0.046)	(0.050)	(0.062)
Constant	7.148***	5.217***	2.501**	2.809**
	(0.824))	(0.989)	(0.999)	(1.400)
Diagnostics Checks				
Observations	2,280	2,280	2,160	2,160
Countries	120	120	120	120
R-squared	0.651	0.692		
Hausman test	25.32***	18.25**		
Time fixed effect	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes
Instruments			19	23
F-test			19.35	27.98
AR1(p)			0.001	0.007
AR2 (p)			0.281	0.307
Hansen (p)			0.466	0.172
Sargan (p)			0.187	0.199

Robust standard errors in parentheses. *, **, *** show 10%, 5%, 1% level of significance, respectively.

production technologies. These businesses may also lack incentives to invest in cleaner technologies, given their primary focus on minimizing costs and avoiding detection by regulatory authorities. Moreover, the lack of institutional oversight and accountability in the informal sector makes it difficult for governments to monitor and enforce environmental compliance. These findings are consistent with previous studies such as Wang

et al. (2019), Huynh (2020), Ahmad and Hussain (2024), and Wang et al. (2024), who similarly document the environmentally detrimental impacts of informal sector activities in developing and emerging economies. The results highlight the importance of integrating environmental considerations into policies aimed at formalizing economic activity and strengthening institutional enforcement mechanisms in developing countries.

To deepen the understanding, we added the squared term of the informal economy and extend our analysis by incorporating interaction terms between the informal economy measures and institutional quality indicators. Specifically, we estimate Equation 2 using both FE and system GMM estimators, focusing on four proxies for institutional quality including COC, ROL, RQ and GE and two measures of informality, the MIMIC index and the DGE-based index. The empirical results are placed in Table 6, which presents sixteen regression models. The main effects of the informal economy remain positive and statistically significant across all models, reaffirming that a higher degree of informality is associated with increased CO₂ emissions. This supports our earlier finding (from Table 5). Importantly, Table 6 confirms that the informal economy has a U-shaped relationship with CO₂ emissions. At lower levels, expansion of informality is associated with rising emissions, reflecting the dominance of outdated technologies, weak compliance, and cost-minimization strategies in the informal sector. However, beyond a certain threshold, the squared term turns negative, suggesting that additional increases in informality may not proportionally raise emissions and can even reduce them. This can be explained by the saturation effect, where further informal activity yields smaller marginal emissions, or by the substitution of cleaner or less energy-intensive practices once informal networks mature. The results match the study of Elgin and Oztunali (2014).

Moreover, the interaction terms between the informal economy and institutional quality measures, including COC, ROL, RQ and GE are consistently negative and statistically significant, indicating that stronger institutions can mitigate the environmental damage caused by informality. For instance, the interaction term between, I.E.,_MIMIC and COC in Model 1 has a coefficient of -0.054 ($p < 0.05$), and between, I.E.,_DGE and COC in Model 2 is -0.045 ($p < 0.10$), implying that improvements in corruption control weaken the positive link between informality and CO₂ emissions. This pattern holds in the dynamic models as well, where the system GMM estimates for the same interactions remain negative and significant (e.g., -0.037 and -0.035 , respectively). Similarly, when institutional quality is measured through ROL, RQ and GE, the interaction terms are similarly negative and significant in both FE and system GMM estimators. These results validate the hypothesis that better institutional quality moderates the adverse effect of the informal economy on environmental degradation in developing countries, supporting the notion of “substitutability” between informal economy and institutional quality. In countries with weak institutions, informality leads to greater environmental degradation; however, where institutions are stronger, they can offset or buffer this effect. This finding is consistent with theoretical arguments and empirical evidence in studies such as Buehn and Schneider (2012), who emphasize the critical role of institutions in shaping the informal economy’s outcomes, and Ahmad and Hussain (2024), and Wang et al. (2024), those highlighted the capacity of governance to manage environmental risks in developing countries. The results offer compelling evidence that while the informal economy exacerbates CO₂ emissions, the presence of strong and effective institutions significantly mitigates this adverse impact. These insights highlight the importance of institutional reforms such as improving legal enforcement, reducing corruption, and enhancing regulatory oversight as part of

comprehensive environmental strategies in developing countries. Rather than relying solely on formalization policies, governments should recognize the potential of institutional strengthening to reduce the ecological footprint of informal activities. The robustness of these results is confirmed through the diagnostic tests. The system GMM estimates satisfy the conditions for valid instrumentation, with no second-order autocorrelation, and acceptable Hansen and Sargan test statistics, confirming instrument validity. The significant lagged dependent variable (CO₂(-1)) in all GMM models further indicates dynamic persistence in environmental outcomes, justifying the use of dynamic panel methods.

To further deepen the empirical analysis, we examine whether the environmental impact of the informal economy varies with different levels of institutional quality, specifically focusing on COC. For this purpose, we estimate Equation 3, incorporating interaction effects at varying thresholds of institutional quality. Table 7 presents the marginal effects of the informal economy measured through both, I.E.,_MIMIC and, I.E.,_DGE on CO₂ emissions at the 25th, 50th, and 75th percentiles of COC, using both FE and system GMM estimation techniques. The results reveal a clear and consistent pattern across all four models: as the level of corruption control improves, the marginal effect of the informal economy on CO₂ emissions declines significantly. At the 25th percentile (i.e., in countries with weak corruption control), the effect of the informal economy on emissions is strongest and statistically significant (e.g., I.E.,_MIMIC = 0.145 under FE and 0.139 under GMM). However, as we move to the 50th percentile, the coefficients drop substantially (e.g., 0.095 and 0.035), and at the 75th percentile, representing stronger COC, the marginal effects become even smaller and, in some cases, even negative (e.g., 0.038 and -0.019). This pattern provides compelling evidence for the conditional role of institutional quality in moderating the environmental consequences of informality. The findings suggest that countries with better institutional quality particularly stronger mechanisms for controlling corruption are better equipped to mitigate the environmental damage caused by informal economy. In these contexts, stricter oversight and improved regulatory capacity likely force even informal actors to comply with environmental norms or transition toward formalization. Theoretically, this result aligns with insights from the institutional and public choice economics literature, which emphasizes that corruption undermines rule enforcement and distorts market incentives. High levels of corruption reduce the effectiveness of environmental policies by allowing polluting firms especially informal ones to bypass regulations through bribery and influence (Dada et al., 2021; Ahmad and Hussain, 2024; Wang et al., 2024). Conversely, when corruption is controlled, informal actors lose the opportunity to externalize costs, leading either to reduced informal activity or better compliance with environmental standards.

We further explore how the rule of law (ROL) conditions the relationship between the informal economy and environmental degradation. The results, presented in Table 8, cover four model specifications using both FE and system GMM estimators. Consistent with expectations, the results show a marked decline in the marginal effect of the informal economy on CO₂ emissions as the ROL strengthens. At the 25th percentile, reflecting weaker legal

TABLE 6 Moderating role of institutional quality in the informal economy and the CO₂ emissions nexus.

Dep. Var: CO ₂	Fixed effects								System GMM							
	COC		ROL		RQ		GE		COC		ROL		RQ		GE	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
CO ₂ (-1)									0.854***	0.974***	0.754***	0.679***	0.972***	0.735***	0.699***	0.973***
									(0.099)	(0.004)	(0.089)	(0.094)	(0.019)	(0.073)	(0.081)	(0.017)
Informal Economy																
I.E.,_MIMIC	0.108**		0.189***		0.091**		0.088**		0.091**		0.089**		0.101*		0.061*	
	(0.051)		(0.009)		(0.043)		(0.041)		(0.039)		(0.045)		(0.059)		(0.034)	
I.E.,_DGE		0.112**		0.129**		0.072**		0.091*		0.103*		0.088***		0.108*		0.122**
		(0.051)		(0.056)		(0.031)		(0.053)		(0.059)		(0.009)		(0.058)		(0.058)
I.E.,_MIMIC ²	-0.034*		-0.078*		-0.058**		-0.019**		0.062*		-0.034**		-0.027**		-0.087*	
	(0.019)		(0.041)		(0.028)		(0.009)		(0.032)		(0.017)		0.013		(0.046)	
I.E.,_DGE ²		-0.051**		-0.049*		-0.029*		-0.072*		-0.028*		-0.048**		-0.019*		-0.045*
		(0.021)		(0.028)		(0.016)		(0.041)		(0.015)		(0.021)		(0.011)		(0.024)
Role of Institutions																
I.E.,_MIMIC × COC	-0.054**								-0.037***							
	(0.022)								(0.005)							
I.E.,_DGE × COC		-0.045*								-0.035*						
		(0.024)								(0.020)						
I.E.,_MIMIC × ROL			-0.064*								-0.099**					
			(0.034)								(0.042)					
I.E.,_DGE × ROL				-0.081**								-0.019**				
				(0.038)								(0.008)				
I.E.,_MIMIC × RQ					-0.019*									-0.048*		
					(0.011)									(0.025)		
I.E.,_DGE × RQ						-0.031*									-0.076**	
						(0.017)									(0.034)	
I.E.,_MIMIC × GE							-0.068*									-0.028*
							(0.036)									(0.015)
I.E.,_DGE × GE								-0.064**								0.061**
								(0.032)								(0.025)
Control Variables																
GDPG	0.123*	0.110**	0.278***	0.189**	0.147**	0.111*	0.178**	0.167*	0.142*	0.135*	0.048*	0.125*	0.172*	0.384**	0.265***	0.132*

(Continued on following page)

TABLE 6 (Continued) Moderating role of institutional quality in the informal economy and the CO₂ emissions nexus.

Dep. Var: CO ₂	Fixed effects								System GMM							
	COC		ROL		RQ		GE		COC		ROL		RQ		GE	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
	(0.067)	(0.051)	(0.081)	(0.079)	(0.072)	(0.061)	(0.075)	(0.092)	(0.075)	(0.073)	(0.025)	(0.067)	(0.089)	(0.191)	(0.092)	(0.077)
FDI	0.055***	0.124*	0.057	0.098**	0.132	0.071*	0.086***	0.097	0.121	0.187**	0.098*	0.104	0.098*	0.104*	0.123***	0.006**
	(0.019)	(0.071)	(0.049)	(0.045)	(0.091)	(0.042)	(0.018)	(0.084)	(0.094)	(0.081)	(0.051)	(0.078)	(0.054)	(0.061)	(0.032)	(0.003)
REC	−0.111*	−0.087**	−0.132**	−0.111*	−0.182*	−0.232**	−0.172	−0.083*	−0.161*	−0.222**	−0.234**	−0.067*	−0.112	−0.118**	−0.174**	−0.198**
	(0.061)	(0.041)	(0.067)	(0.062)	(0.099)	(0.098)	(0.108)	(0.045)	(0.087)	(0.089)	(0.099)	(0.036)	(0.075)	(0.059)	(0.074)	(0.091)
POPG	0.076***	0.158	0.045*	0.078*	0.037*	0.027	0.065**	0.064**	0.069	0.038*	0.089	0.078*	0.085	0.094	0.082**	0.159
	(0.008)	(0.123)	(0.024)	(0.045)	(0.019)	(0.021)	(0.032)	(0.030)	(0.046)	(0.021)	(0.087)	(0.045)	(0.058)	(0.072)	(0.041)	(0.431)
Constant	5.254***	4.192***	4.212***	3.754**	4.215**	6.211***	5.287***	3.546***	2.451**	1.123	1.463*	1.069***	1.154	2.012**	1.546*	1.035*
	(0.864)	(0.911)	(0.989)	(1.611)	(1.983)	(0.858)	(1.581)	(0.672)	(0.989)	(0.762)	(0.817)	(0.031)	(0.894)	(0.875)	(0.879)	(0.613)
Diagnostics Checks																
Observations	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,160	2,160	2,160	2,160	2,160	2,160	2,160	2,160
Countries	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
R-squared	0.621	0.690	0.512	0.597	0.678	0.523	0.621	0.561								
Hausman test	24.12**	27.19**	22.65**	21.28***	18.23**	16.36***	18.65**	17.35*								
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Instruments									33	31	35	32	34	29	34	38
F-test									25.83	21.72	20.98	28.35	19.25	20.54	16.25	19.25
AR1 (p)									0.005	0.000	0.013	0.002	0.000	0.002	0.009	0.004
AR2 (p)									0.663	0.781	0.638	0.644	0.845	0.458	0.652	0.542
Hansen (p)									0.315	0.567	0.523	0.637	0.352	0.521	0.365	0.145
Sargan (p)									0.276	0.432	0.172	0.387	0.321	0.542	0.254	0.652

Same as Table 5.

TABLE 7 Conditional impact of the informal economy on CO₂ emissions at different levels of control of corruption.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
COC at P25	0.145*	0.121*	0.139***	0.098*
	(0.084)	(0.071)	(0.024)	(0.051)
COC at P50	0.095**	0.067**	0.035*	0.039**
	(0.045)	(0.031)	(0.021)	(0.018)
COC at P75	0.038**	0.018*	−0.019*	−0.008**
	(0.019)	(0.011)	(0.011)	(0.004)

P25, P50, and P75 are the 25th, 50th and 75th percentiles respectively. *, **, *** indicate significant at 10%, 5%, 1%, respectively.

TABLE 8 Conditional impact of the informal economy on CO₂ emissions at different levels of the rule of law.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
ROL at P25	0.170***	0.156**	0.097***	0.111*
	(0.022)	(0.065)	(0.021)	(0.061)
ROL at P50	0.079*	0.098*	0.025**	0.076**
	(0.048)	(0.054)	(0.011)	(0.034)
ROL at P75	0.020**	0.025*	−0.009**	−0.016*
	(0.008)	(0.013)	(0.004)	(0.008)

Same as Table 7.

institutions, the informal economy significantly and positively influences CO₂ emissions. However, at the 50th percentile, the impact reduces substantially, while at the 75th percentile, representing stronger legal systems, the effect of informality on emissions diminishes further and even turns slightly negative in system GMM models, indicating a potentially neutralizing or mitigating effect. These findings underscore the critical role of a robust ROL in mitigating the environmental harm caused by informal economic activities. A strong ROL ensures that environmental and economic regulations are enforced consistently and predictably, reducing regulatory uncertainty. This stability encourages informal businesses to formalize, thereby subjecting them to environmental standards and oversight. As a result, firms are incentivized to adopt cleaner and more sustainable practices, leading to reduced CO₂ emissions overall. The empirical results also resonate with recent studies such as Butt et al. (2024), and Wang et al. (2024), who highlight that improved ROL promotes formalization and environmental compliance, thereby reducing pollution. This link is vital for developing countries where informal economies are large and institutional weaknesses often prevail.

Similarly, Tables 9, 10 reveal that the informal economy exerts a strong positive effect on CO₂ emissions when regulatory quality (RQ) and government effectiveness (GE) are weak (25th percentile). However, as these institutional dimensions improve to median and higher levels (50th and 75th percentiles), the marginal effect of

informality on emissions declines significantly and even turns neutral or negative under the system GMM estimates. This implies that weak institutions allow informal firms to operate with outdated technologies, evade compliance, and externalize environmental costs, thereby amplifying emissions. In contrast, stronger RQ and GE enhance policy enforcement, reduce opportunities for evasion, and incentivize cleaner practices, which in turn neutralize the environmental damage from informality. These results are consistent with Legalist theory by De Soto (1989), De Soto (2000), which posits that effective institutions internalize externalities and align private incentives with social welfare.

4.3.1 Robustness check

To verify the robustness of our findings, we replace CO₂ emissions with greenhouse gas (GHG) emissions as the measure of environmental degradation, keeping all other variables and estimation methods unchanged. The results, presented in Table 11, confirm that the informal economy significantly increases GHG emissions across all four estimated models. These findings are consistent with our baseline results using CO₂ emissions and support the hypothesis that the informal economy contributes to environmental degradation in developing countries. Diagnostic tests, including AR(1), AR(2), Hansen, and Sargan, indicate that the system GMM models are well specified and reliable. Moreover, the Hausman test indicates that the FE models are reliable. Overall, this

TABLE 9 Conditional impact of the informal economy on CO₂ emissions at different levels of regularity quality.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
RQ at P25	0.211***	0.117**	0.184***	0.098*
	(0.064)	(0.052)	(0.025)	(0.051)
RQ at P50	0.149**	0.066***	0.101*	0.039**
	(0.084)	(0.016)	(0.052)	(0.018)
RQ at P75	0.087**	0.011**	0.051**	−0.008**
	(0.041)	(0.005)	(0.021)	(0.004)

Same as Table 7.

TABLE 10 Conditional impact of the informal economy on CO₂ emissions at different levels of government effectiveness.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
GE at P25	0.101***	0.184***	0.177***	0.089*
	(0.052)	(0.021)	(0.014)	(0.052)
GE at P50	0.054**	0.117**	0.109**	0.031***
	(0.024)	(0.052)	(0.049)	(0.004)
GE at P75	0.012*	0.066*	0.063***	−0.002**
	(0.007)	(0.039)	(0.023)	(0.001)

Same as Table 7.

robustness analysis strengthens the credibility of our main conclusions by demonstrating that the adverse impact of the informal economy on environmental degradation holds regardless of the environmental degradation proxy used.

To further validate our findings, we examine the U-shape relationship and moderating role of institutional quality in the relationship between the informal economy and GHG emissions. Table 12 shows that the squared terms of informal economy measures reveal a U-shape relationship with GHG emissions. Moreover, interaction terms between the informal economy (I.E.,_MIMIC, I.E.,_DGE) and institutional indicators (COC, ROL, RQ and GE) are consistently negative and statistically significant across both FE and system GMM models. These results indicate that stronger institutional quality through improved COC, ROL, RQ and GE reduces the environmental harm associated with informal activities. In other words, better institutions weaken the positive effect of informality on GHG emissions by encouraging compliance and discouraging informal practices. The findings support our hypothesis and are consistent with earlier results based on CO₂ emissions (Table 6), reaffirming that institutional quality plays a crucial moderating role in mitigating the environmental impact of informality in developing countries.

To further explore the conditional relationship, we estimate Equation 3, assessing the marginal impact of the informal economy on GHG emissions at different levels of COC, specifically at the 25th,

50th, and 75th percentiles. As shown in Table 13, the marginal effect of the informal economy (I.E.,_MIMIC, I.E.,_DGE) on GHG emissions consistently declines as COC improves across both FE and system GMM estimations. These results confirm that stronger COC mitigates the environmental impact of informal activities by reducing incentives to operate outside regulatory frameworks. The findings are consistent with earlier results in Table 7, reinforcing the moderating role of institutional quality in limiting environmental degradation driven by informality.

To evaluate the moderating role of the ROL, we examine the marginal effects of the informal economy on GHG emissions at the 25th, 50th, and 75th percentiles of ROL. As shown in Table 14, the coefficients for both, I.E.,_MIMIC and, I.E.,_DGE decline progressively across all percentiles in both FE and system GMM estimations. These results suggest that stronger legal institutions significantly weaken the environmental impact of informality. As ROL improves, firms are more likely to operate within the formal sector and comply with environmental standards, leading to lower GHG emissions. The findings are consistent with the earlier CO₂-based analysis (Table 8), reinforcing the role of institutional quality in mitigating the adverse ecological effects of the informal economy.

Similarly, Tables 15, 16 show that the informal economy significantly increases GHG emissions when regulatory quality and government effectiveness are weak, but this adverse impact diminishes considerably as institutional strength improves. These results align with Tables 9, 10, confirming that stronger institutions

TABLE 11 Impact of the informal economy on GHG emissions.

Dep. Var: GHG	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
GHG (–1)			0.867***	0.916***
			(0.056)	(0.036)
Informal Economy				
I.E.,_MIMIC	0.111**		0.176***	
	(0.054)		(0.019)	
I.E.,_DGE		0.094*		0.214**
		(0.049)		(0.091)
Control Variables				
GDPG	0.345***	0.172*	0.108**	0.197**
	(0.081)	(0.091)	(0.048)	(0.089)
FDI	0.076*	0.089	0.115**	0.103*
	(0.044)	(0.075)	(0.053)	(0.061)
REC	0.248**	0.187*	0.145*	0.111**
	(0.099)	(0.098)	(0.078)	(0.051)
POPG	0.059	0.087**	0.112**	0.078*
	(0.042)	(0.042)	(0.056)	(0.042)
Constant	5.712***	7.402**	3.871*	2.465***
	(0.975)	(2.981)	(1.977)	(0.758)
Diagnostics Checks				
Observations	2,280	2,280	2,160	2,160
Countries	120	120	120	120
R-squared	0.692	0.772		
Hausman test	15.21**	21.24**		
Time fixed effect	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes
Instruments			24	27
F-test			27.98	76.18
AR1 (p)			0.003	0.012
AR2 (p)			0.261	0.481
Hansen (p)			0.283	0.571
Sargan (p)			0.393	0.742

Same as Table 5.

consistently moderate the environmental harm of informality. Weak institutions enable firms to externalize pollution costs, while better regulation and governance enhance enforcement and incentives for compliance, thereby reducing the ecological footprint of informal activities.

Our empirical analysis also incorporates four control variables in all the estimated models: GDP growth, FDI, renewable energy

consumption, and population growth. The results indicate that GDP growth significantly exacerbates both CO₂ and GHG emissions, reinforcing the environmental concerns associated with economic expansion, as noted by [Shaari et al. \(2021\)](#). FDI similarly exerts a positive and significant effect on both emissions, suggesting a pollution-intensive pattern of investment in developing countries, consistent with [Zmami and Ben-Salha \(2020\)](#) and [Huang et al.](#)

TABLE 12 Moderating role of institutional quality in the informal economy and GHG emissions nexus.

Dep. Var: GHG	Fixed effects								System GMM							
	COC		ROL		RQ		GE		COC		ROL		RQ		GE	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
GHG (–1)									0.927***	0.674***	0.724***	0.832***	0.854***	0.654***	0.758***	0.768***
									(0.078)	(0.085)	(0.058)	(0.082)	(0.091)	(0.089)	(0.082)	(0.082)
Informal Economy																
I.E.,_MIMIC	0.119**		0.134**		0.102*		0.087*		0.141*		0.078*		0.154**		0.125**	
	(0.064)		(0.055)		(0.056)		(0.045)		(0.078)		(0.041)		(0.071)		(0.062)	
I.E.,_DGE		0.088**		0.094**		0.211**		0.105**		0.098*		0.061**		0.078**		0.121*
		(0.043)		(0.042)		(0.097)		(0.053)		(0.054)		(0.030)		(0.039)		(0.069)
I.E.,_MIMIC ²	–0.089*		–0.112*		–0.072**		–0.048*		–0.088*		–0.039*		–0.111**		–0.091*	
	(0.051)		(0.058)		(0.031)		(0.028)		(0.049)		(0.021)		(0.051)		(0.051)	
I.E.,_DGE ²		–0.148*		–0.057**		–0.152*		–0.038**		–0.058*		–0.032*		–0.067**		–0.074*
		(0.078)		(0.025)		(0.081)		(0.018)		(0.031)		(0.018)		(0.027)		(0.042)
Role of Institutions																
I.E.,_MIMIC × COC	–0.046**								–0.011**							
	(0.022)								(0.005)							
I.E.,_DGE × COC		–0.027**								–0.021*						
		(0.012)								(0.013)						
I.E.,_MIMIC × ROL			–0.086*								–0.024*					
			(0.045)								(0.014)					
I.E.,_DGE × ROL				–0.023*								–0.045*				
				(0.012)								(0.023)				
I.E.,_MIMIC × RQ					–0.112**								–0.064**			
					(0.045)								(0.026)			
I.E.,_DGE × RQ						–0.121*								–0.029*		
						(0.063)								(0.015)		
I.E.,_MIMIC × GE							–0.053**								–0.098**	
							(0.022)								(0.041)	
I.E.,_DGE × GE								–0.027*								–0.057*
								(0.014)								(0.032)
Control Variables																
GDPG	0.124**	0.096*	0.165*	0.116	0.299**	0.187***	0.084*	0.127***	0.119*	0.157*	0.091	0.132*	0.272***	0.138**	0.141*	0.112*

(Continued on following page)

TABLE 12 (Continued) Moderating role of institutional quality in the informal economy and GHG emissions nexus.

Dep. Var: GHG	Fixed effects								System GMM							
	COC		ROL		RQ		GE		COC		ROL		RQ		GE	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
	(0.054)	(0.055)	(0.089)	(0.088)	(0.146)	(0.071)	(0.051)	(0.008)	(0.067)	(0.085)	(0.081)	(0.068)	(0.047)	(0.059)	(0.081)	(0.058)
FDI	0.091*	0.074*	0.085	0.103*	0.059	0.081*	0.057*	0.083	0.121*	0.127**	0.093*	0.058***	0.045*	0.116*	0.058**	0.125
	(0.051)	(0.039)	(0.081)	(0.059)	(0.049)	(0.045)	(0.032)	(0.074)	(0.065)	(0.054)	(0.054)	(0.009)	(0.024)	(0.067)	(0.029)	(0.087)
REC	−0.074*	−0.083**	−0.093*	−0.132	−0.124*	−0.137*	−0.084	0.138*	−0.078**	−0.102	−0.092*	0.124	−0.152**	−0.138**	−0.089	−0.079*
	(0.045)	(0.038)	(0.049)	(0.089)	(0.067)	(0.078)	(0.081)	(0.071)	(0.039)	(0.071)	(0.051)	(0.098)	(0.067)	(0.068)	(0.067)	(0.042)
POPG	0.049*	0.092	0.072*	0.083*	0.052*	0.027*	0.087	0.057**	0.112*	0.090	0.118*	0.092*	0.083*	0.097*	0.112	0.103*
	(0.028)	(0.081)	(0.038)	(0.045)	(0.028)	(0.014)	(0.061)	(0.028)	(0.059)	(0.069)	(0.064)	(0.048)	(0.043)	(0.058)	(0.089)	(0.058)
Constant	6.701**	4.125**	5.254***	3.251**	4.113***	4.281*	3.985	5.325***	1.345*	0.965**	2.315**	0.658*	0.804**	1.254***	2.548***	1.365*
	(2.811)	(1.991)	(0.584)	(1.612)	(0.641)	(2.215)	(2.588)	(0.986)	(0.812)	(0.411)	(0.991)	(0.411)	(0.343)	(0.089)	(0.325)	(0.751)
Diagnostics Checks																
Observations	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,160	2,160	2,160	2,160	2,160	2,160	2,160	2,160
Countries	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
R-squared	0.492	0.561	0.652	0.576	0.632	0.598	0.658	0.577								
Hausman test	18.21**	16.38***	21.32**	27.12**	22.32**	17.32**	20.85**	15.32**								
Time fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Instruments									25	22	20	28	24	28	21	27
F-test									18.98	28.09	28.97	39.65	18.32	24.25	21.38	27.21
AR1 (p)									0.007	0.014	0.003	0.000	0.005	0.000	0.007	0.008
AR2 (p)									0.493	0.286	0.873	0.592	0.654	0.765	0.458	0.652
Hansen (p)									0.173	0.271	0.154	0.542	0.254	0.587	0.234	0.149
Sargan (p)									0.372	0.634	0.362	0.832	0.547	0.652	0.426	0.325

Same as Table 5.

TABLE 13 Conditional impact of the informal economy on GHG emissions at different levels of control of corruption.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
COC at P25	0.142**	0.209**	0.109**	0.076***
	(0.064)	(0.089)	(0.051)	(0.020)
COC at P50	0.089**	0.154**	0.059*	0.017**
	(0.042)	(0.071)	(0.031)	(0.008)
COC at P75	0.026**	0.098**	0.019*	−0.003**
	(0.013)	(0.041)	(0.009)	(0.001)

Same as Table 7.

TABLE 14 Conditional impact of the informal economy on GHG emissions at different levels of rule of law.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
ROL at P25	0.138**	0.114**	0.095*	0.089***
	(0.061)	(0.051)	(0.051)	(0.019)
ROL at P50	0.071*	0.069**	0.031**	0.025**
	(0.037)	(0.031)	(0.014)	(0.012)
ROL at P75	0.018*	0.013**	−0.009**	−0.006**
	(0.009)	(0.006)	(0.004)	(0.003)

Same as Table 7.

TABLE 15 Conditional impact of the informal economy on GHG emissions at different levels of regularity quality.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
RQ at P25	0.079*	0.111**	0.098***	0.123*
	(0.042)	(0.054)	(0.015)	(0.064)
RQ at P50	0.041***	0.087*	0.056**	0.088*
	(0.008)	(0.045)	(0.025)	(0.051)
RQ at P75	0.012**	0.035*	0.025**	0.038*
	(0.006)	(0.021)	(0.011)	(0.022)

Same as Table 7.

TABLE 16 Conditional impact of the informal economy on GHG emissions at different levels of government effectiveness.

Percentile levels	Fixed effects		System GMM	
	I.E.,_MIMIC	I.E.,_DGE	I.E.,_MIMIC	I.E.,_DGE
GE at P25	0.210**	0.157*	0.098**	0.118**
	(0.098)	(0.088)	(0.042)	(0.052)
GE at P50	0.145*	0.101*	0.059*8	0.071*
	(0.078)	(0.058)	(0.025)	(0.038)
GE at P75	0.087*	0.053*	0.019**	0.025*
	(0.049)	(0.031)	(0.008)	(0.015)

Same as Table 7.

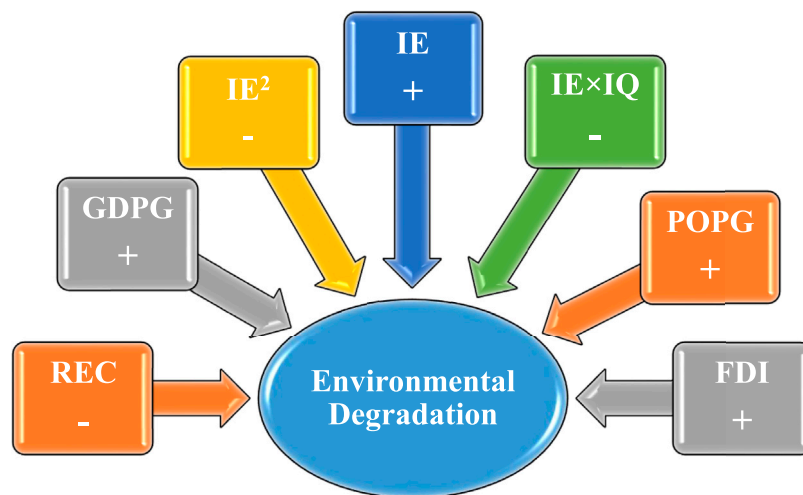


FIGURE 3
The graphical conclusion. Source: Author's own construction.

(2022). In contrast, renewable energy usage consistently demonstrates a negative and highly significant relationship with CO₂ and GHG emissions, underscoring its pivotal role in mitigating environmental degradation, as supported by Shafiei and Salim (2014). Additionally, population growth is positively and significantly associated with increased CO₂ and GHG emissions, corroborating the findings of Ohlan (2015) and highlighting demographic pressure as a key driver of environmental stress.

5 Conclusion and policy implications

Environmental degradation poses a critical challenge for developing countries, where weak institutional structures often permit the expansion of informal economic activities. The informal sector, operating outside formal oversight, frequently engages in environmentally harmful practices such as illegal resource extraction, unregulated emissions, and improper waste disposal. These activities not only undermine environmental sustainability but also circumvent national and international environmental standards. This study makes a significant contribution to the literature by empirically examining the impact of the informal economy on environmental degradation measured through CO₂ and GHG emissions across 120 developing countries. It further explores the U-shape relationship and the moderating role of institutional quality, specifically focusing on the control of corruption, rule of law, regulatory quality, and government effectiveness. Our findings consistently reveal that the informal economy exacerbates environmental degradation, supporting the hypothesis that its unregulated nature contributes to ecological harm.

Importantly, the results revealed a U-shape relationship between informal economy and environmental degradation. Furthermore, the institutional quality emerges as a critical mitigating factor. The interaction terms in our empirical models indicate that stronger institutions characterized by more effective control of corruption, rule of law, regularity quality, and government effectiveness

significantly reduce the negative environmental impacts of informal economic activity. This suggests that institutional quality not only constrains the scale of informality but also limits its environmental footprint by encouraging greater compliance with environmental regulations and norms. The robustness of our results, confirmed through alternative measures of both informality (MIMIC and DGE approaches) and environmental degradation (CO₂ and GHG emissions), underscores the reliability of these conclusions. Furthermore, marginal effects analysis demonstrates that as institutional quality improves, the environmental harm linked to informality declines, reinforcing the value of institutional strengthening.

This study matches several important parts of the Sustainable Development Goals (SDGs), including SDG 8 (Decent Work and Economic Growth), SDG 13 (Climate Action) and SDG 16 (Peace, Justice and Strong Institutions), by linking informal economy, institutional quality and environmental degradation. It points out that sustainable development needs joint efforts that go beyond different sectors because economic informality, how governments are run, and environmental wellbeing are highly connected. The conclusion of the study is also presented in Figure 3.

5.1 Policy implications

The findings demonstrate that the informal economy significantly contributes to CO₂ and GHG emissions in developing countries, but the adverse effects are mitigated when institutional quality, particularly regulatory quality, government effectiveness, rule of law, and corruption control, is stronger. These results carry several concrete policy implications. First, governments should target the most polluting informal activities, such as brick kilns, leather tanning, small-scale mining, and unregulated manufacturing, by introducing low-cost cleaner technology adoption schemes. For example, subsidizing modern kilns or eco-friendly tanning processes can directly reduce emissions while ensuring that informal operators remain competitive. Second,

the results show that stronger institutions offset informality's environmental harm. Thus, rather than broad governance reforms, countries should focus on sector-specific enforcement mechanisms, for instance, mobile environmental inspection units for informal industries in South Asia or digital monitoring of small-scale firms in Africa. These targeted institutional interventions can reduce enforcement gaps without overburdening weak bureaucracies. Third, given the high persistence of emissions found in our dynamic models, policies must be results-oriented and continuous rather than one-off initiatives. A promising approach is the gradual formalization-through-incentives strategy: offering tax credits, microfinance, or market access benefits to informal firms that adopt cleaner practices. This aligns private incentives with social benefits, making compliance less costly than avoidance.

Fourth, since our results highlight a U-shaped effect of informality, policymakers should avoid overly strict regulations that unintentionally push firms further into the informal sector. Instead, "smart regulation" lighter compliance requirements for small firms, combined with strict penalties for repeat polluters, can minimize the regulatory burden while still reducing emissions. Finally, cross-country evidence suggests that regional cooperation is essential. Many developing countries face similar problems, such as shared river basins polluted by informal industries or cross-border trade in informal goods. Regional frameworks for cleaner technologies and environmental monitoring, particularly within African and Asian regional blocs, would enhance the effectiveness of national policies. In sum, our results suggest that tackling the environmental consequences of informality requires integrated strategies: targeted clean technology programs, sector-specific institutional enforcement, incentive-based formalization, smart regulation, and regional cooperation. These measures go beyond generic governance reforms and directly address the mechanisms through which informality harms the environment, thereby offering actionable pathways for developing countries to achieve both sustainability and formalization.

5.2 Future research

Our study suggests different avenues for future research. One potential direction is sector-specific analysis, where future studies could focus on different sectors within the informal economy, such as agriculture, energy, or manufacturing, to better understand their different contributions to environmental degradation. This approach could help develop more targeted policy recommendations. Another important area for future research is conducting longitudinal studies to explore how institutional quality, informal economy, and environmental degradation relationships change over time. Future studies could examine the long-term effects of institutional reforms on these dynamics. Additionally, future research could assess the impact of specific policy interventions to enhance institutional quality and reduce the impact of the informal economy on pollution emissions. Comparative studies between countries that have implemented such policies and those that have not could provide valuable insights into best practices.

Expanding the geographic scope to include developed countries with significant informal economy would also contribute to a more comprehensive global understanding of the informal economy impact on environmental degradation and the role of institutional quality in mitigating it. Although we focused on four key institutional indicators, including control of corruption, rule of law, regulatory quality, and government effectiveness, future studies could expand the analysis by incorporating additional indicators of institutional quality, such as political stability, voice, and accountability. Moreover, the use of a composite institutional index could provide a broader picture of governance quality and allow for testing whether aggregate institutional strength has a stronger moderating role compared to individual components.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

CS: Validation, Funding acquisition, Project administration, Data curation, Supervision, Resources, Conceptualization, Writing – original draft, Methodology, Software, Visualization, Investigation, Writing – review and editing, Formal Analysis. FH: Writing – original draft, Formal Analysis, Writing – review and editing, Supervision, Funding acquisition, Data curation, Software, Investigation, Project administration, Conceptualization, Resources, Validation, Visualization, Methodology. VA: Supervision, Methodology, Validation, Conceptualization, Project administration, Investigation, Data curation, Funding acquisition, Writing – review and editing, Writing – original draft, Formal Analysis, Software, Resources, Visualization. WA: Funding acquisition, Project administration, Resources, Visualization, Validation, Formal Analysis, Writing – original draft, Investigation, Supervision, Data curation, Writing – review and editing, Conceptualization, Methodology, Software. CF: Writing – review and editing, Writing – original draft, Supervision, Investigation, Formal Analysis, Software, Funding acquisition, Project administration, Resources, Methodology, Data curation, Visualization, Validation, Conceptualization. NC: Investigation, Supervision, Formal Analysis, Methodology, Data curation, Writing – review and editing, Software, Writing – original draft, Conceptualization, Resources, Funding acquisition, Validation, Visualization, Project administration. FA: Investigation, Resources, Visualization, Funding acquisition, Software, Data curation, Formal Analysis, Conceptualization, Writing – review and editing, Validation, Supervision, Project administration, Methodology, Writing – original draft. MZ: Funding acquisition, Supervision, Writing – original draft, Software, Writing – review and editing, Formal Analysis, Investigation, Resources, Visualization, Data curation, Methodology, Project administration, Conceptualization, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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