

DOI: 10.5281/zenodo.124261044

# EXPLORING THE EFFECTS OF DIGITAL TRANSFORMATION AND LOCAL INVESTMENTS ON ENVIRONMENTAL DEGRADATION IN THE KINGDOM OF SAUDI ARABIA

Sonia Mannai<sup>1\*</sup>, Samira Youssef Brahmia<sup>2</sup>

<sup>1</sup> Department of Finance and Investment, Faculty of Business Administration, University of Tabuk, Tabuk 71491, KSA; s\_almanae@ut.edu.sa. ORCID: 0009-0002-5937-0949

<sup>2</sup> Department of Finance and Investment, Faculty of Business Administration, University of Tabuk, Tabuk 71491, KSA; Sbrahmyah@ut.edu.sa. ORCID: 0009-0008-4083-8138

Received: 31/12/2025

Accepted: 27/04/2026

Corresponding Author: Sonia Mannai  
(s\_almanae@ut.edu.sa)

## ABSTRACT

*This study examines the effects of digital transformation and local investment on environmental degradation in the Kingdom of Saudi Arabia over the period 1990–2024. Using CO<sub>2</sub> emissions per capita as a proxy for environmental degradation, the study incorporates digital transformation, gross capital formation, trade openness, urbanization, and foreign direct investment within an autoregressive distributed lag (ARDL) framework. The unit root results indicate a mixed order of integration among the variables, supporting the suitability of the ARDL bounds-testing approach. The bounds test confirms the existence of a stable long-run relationship among the variables. The error correction model further shows that short-run disequilibrium adjusts gradually toward long-run equilibrium, with approximately 24.2% of deviations corrected annually. The empirical findings reveal that gross capital formation has a positive and significant effect on CO<sub>2</sub> emissions, suggesting that local investment remains associated with energy-intensive expansion rather than green transformation. Foreign direct investment shows a mixed short-run pattern, with a weak negative contemporaneous effect but a positive and significant lagged effect, indicating that its environmental impact becomes more visible after investment projects become operational. Urbanization does not exert a statistically significant short-run effect. The findings highlight the need to align investment and digital transformation strategies with cleaner technologies, energy-efficient infrastructure, and Saudi Arabia's environmental sustainability objectives.*

---

**KEYWORDS:** Digital transformation; Local investment; CO<sub>2</sub> emissions; ARDL; Saudi Arabia.

---

## 1. INTRODUCTION

Environmental degradation has become one of the most pressing challenges facing modern economies, particularly those seeking to achieve rapid growth and structural transformation. As development expands through industrial activity, infrastructure, trade, and urbanization, environmental pressures tend to intensify unless sustainable policies and cleaner technologies support growth. Among the various indicators used to capture environmental deterioration, carbon dioxide (CO<sub>2</sub>) emissions remain one of the most widely accepted proxies because they reflect the environmental consequences of production, energy use, transportation, and investment activity. Accordingly, understanding the determinants of CO<sub>2</sub> emissions has become essential for countries attempting to balance economic progress with environmental sustainability.

In recent years, attention has increasingly shifted toward the environmental implications of digital transformation. Digital transformation is now a central component of economic modernization, influencing production processes, service delivery, communication systems, and patterns of consumption. Its effect on the environment, however, is not unidirectional. On the one hand, digitalization can improve environmental quality by promoting efficiency, supporting smart systems, reducing waste, optimizing logistics, and enabling better monitoring of resource use. On the other hand, the expansion of digital infrastructure, data centers, electronic devices, and technology-intensive activities may increase electricity consumption and, consequently, carbon emissions, especially in economies where conventional energy sources remain dominant. This duality makes the relationship between digital transformation and environmental degradation an important empirical question rather than a matter that can be resolved theoretically alone.

Investment also occupies a central position in the environment–development nexus. Local investment, commonly proxied by gross capital formation, is vital for expanding productive capacity, upgrading infrastructure, and stimulating long-term growth. Yet its environmental effect depends largely on the sectors in which investment is concentrated and the type of technologies it supports. Investment directed toward sustainable infrastructure, cleaner production, and efficient technologies may help reduce environmental damage. In contrast, investment flowing into carbon-intensive industries, conventional construction, and energy-demanding activities may worsen environmental degradation. Similarly, foreign direct investment may generate beneficial outcomes through technology transfer and

improved managerial practices, but it may also raise emissions if it expands pollution-intensive activities. Trade openness and urbanization add further complexity, as both may either enhance efficiency and modernization or increase environmental stress through greater production, transport demand, and resource consumption.

These issues are particularly relevant in the context of the Kingdom of Saudi Arabia. The Saudi economy has been undergoing substantial transformation, characterized by diversification efforts, digital expansion, increasing investment activity, urban development, and deeper integration into the global economy. At the same time, environmental sustainability has become increasingly important within the national development agenda. This creates a critical policy question: whether the Kingdom's ongoing economic and technological transformation is contributing to environmental degradation or helping to mitigate it. The answer is not straightforward. While digital development and investment can promote modernization and efficiency, they can also increase environmental pressure if they are associated with greater energy demand and carbon-intensive growth patterns. Therefore, examining these relationships in the Saudi context is both timely and necessary.

Despite the growing literature on environmental degradation, much of the existing research continues to focus on traditional determinants such as economic growth, energy consumption, and industrialization. Compared with other regions, less attention has been paid to the environmental role of digital transformation, particularly in developing and transition-oriented economies. In the Saudi case, the available literature has generally emphasized energy-related and macroeconomic drivers of emissions, while limited attention has been paid to the combined influence of digital transformation, local investment, foreign direct investment, trade openness, and urbanization within a unified analytical framework. This leaves an important gap in the literature, especially given the increasing centrality of digitalization and investment policies in the Kingdom's broader development strategy.

Against this background, the present study examines the effects of digital transformation and local investment on environmental degradation in the Kingdom of Saudi Arabia, while also incorporating trade openness, urban population, gross capital formation, and foreign direct investment as explanatory factors. CO<sub>2</sub> emissions per capita are used as a proxy for environmental degradation because they provide a direct and widely recognized

measure of environmental pressure associated with economic activity. By analyzing these variables together, the study seeks to provide a clearer understanding of how technological change and investment dynamics shape environmental outcomes in Saudi Arabia.

The study is important for both academic and policy reasons. Academically, it contributes to the emerging literature on the digitalization–environment nexus by assessing whether digital transformation in Saudi Arabia is environmentally beneficial or environmentally harmful. It also deepens the investment–environment debate by considering both domestic and foreign investment alongside other structural variables that influence emissions. From a policy perspective, the findings may help decision-makers better align digital transformation and investment strategies with environmental sustainability goals. In this way, the study contributes to a more informed understanding of how Saudi Arabia can pursue modernization while more effectively managing its environmental challenges.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on environmental degradation and its macroeconomic determinants, with particular attention to digital transformation, local investment, trade openness, urbanization, and foreign direct investment. Section 3 presents the data, variable definitions, and model specification. Section 4 outlines the econometric methodology employed in the analysis. Section 5 reports and discusses the empirical results. Finally, Section 6 concludes the study and provides policy implications based on the main findings.

## 2. LITERATURE REVIEW

### 2.1 Environmental degradation and macroeconomic transformation

Recent literature increasingly treats environmental degradation in Saudi Arabia as a macroeconomic outcome linked to the structure of growth, energy dependence, openness, and ongoing economic transformation. Rather than viewing carbon emissions as a purely environmental issue, current studies show that emissions are closely tied to the way growth is generated and sustained. For example, Tahir et al. (2024) find that energy consumption, GDP per capita, and foreign direct investment worsen environmental quality in Saudi Arabia, while Khan and Khan (2024) report a long-run relationship between energy consumption, economic growth, and carbon emissions. In a related study, Alnagar et al. (2026) show that GDP, energy exports, and non-

renewable energy increase CO<sub>2</sub> emissions, whereas renewable energy, financial development, and trade openness help reduce them. Together, these findings suggest that environmental degradation in Saudi Arabia is closely embedded in the country's broader macroeconomic and structural dynamics rather than being driven by a single isolated factor.

More recent evidence reinforces this interpretation by showing that the composition of growth matters as much as its scale. Tili et al. (2025) demonstrate that oil-driven growth intensifies emissions in Saudi Arabia, whereas non-oil activities reduce them, highlighting the environmental importance of economic diversification. Similarly, Binsuwadan et al. (2025) find that economic growth and energy consumption significantly increase CO<sub>2</sub> emissions, confirming that expansion remains environmentally costly when it relies on carbon-intensive energy use. Ben-Ahmed et al. (2025) likewise document a significant long-run relationship between CO<sub>2</sub> emissions and the renewable/non-renewable energy mix in Saudi Arabia, further linking environmental degradation to the country's evolving energy transition. These studies collectively indicate that macroeconomic transformation in the Kingdom cannot be assessed independently of its environmental implications, especially where growth remains intertwined with energy structure and resource use.

The broader macroeconomic literature points in the same direction. Omar et al. (2025), using panel VAR evidence from 78 countries, show that GDP and trade shocks significantly increase CO<sub>2</sub> emissions, suggesting that environmental outcomes are highly sensitive to macroeconomic disturbances. In the Saudi case specifically, Benzerrouk et al. (2026) show that globalization, economic growth, and trade openness exert significant nonlinear effects on environmental degradation, with asymmetric impacts across positive and negative shocks. Taken together, this recent body of research suggests that environmental degradation in Saudi Arabia is best understood as a by-product of macroeconomic transformation, particularly the interaction among growth composition, globalization, energy dependence, and structural change.

### 2.2. Digital transformation and environmental degradation

The literature increasingly identifies digital transformation as an important, but theoretically ambiguous, determinant of environmental degradation. On the one hand, digitalization can improve environmental quality by enhancing

production efficiency, optimizing resource allocation, supporting green innovation, and facilitating industrial upgrading. Several recent studies show that the digital economy can reduce carbon-emission intensity through better energy efficiency, structural transformation, and improved carbon-emission efficiency (Lyu et al., 2024; Xia et al., 2025; Wang & Gao, 2025; Song et al., 2025).

On the other hand, the literature also shows that digital transformation may worsen environmental outcomes under certain conditions. Rising electricity demand, expanding digital infrastructure, and scale effects associated with digitally enabled production can increase emissions, even when efficiency gains are present. Recent evidence indicates that digitalization may raise trade-adjusted carbon emissions, produce rebound effects, and in some cases increase total emissions despite lowering carbon intensity at the firm level (Akdemir Ömür & Erkasap, 2025; Qian et al., 2025; Chen & Xu, 2025; Wang et al., 2025). These findings suggest that the environmental effect of digital transformation depends on the energy mix, the type of digital expansion, and the institutional context in which digital technologies are adopted.

In the Saudi context, the empirical literature remains limited but increasingly relevant. Recent studies suggest that digitalization is becoming an important component of sustainable development and green growth in the Kingdom, although the precise direction of its effect on CO<sub>2</sub> emissions is not yet fully settled (Ahmed et al., 2025; Khemiri & Neffati, 2025). Therefore, the Saudi case still requires further empirical investigation to determine whether digital transformation serves as an environmentally improving force or an additional source of environmental pressure.

### **2.3 Local investment and environmental degradation**

Local investment, commonly proxied by gross capital formation, is an important determinant of environmental degradation because it reflects domestic capital accumulation, infrastructure expansion, and production upgrading. Its environmental effect is theoretically ambiguous. On the one hand, higher capital formation may increase CO<sub>2</sub> emissions when investment is directed toward construction, heavy industry, transport, and other energy-intensive activities. On the other hand, it may improve environmental quality when it supports cleaner technologies, energy-efficient infrastructure, and low-carbon production systems. This duality explains why recent studies increasingly treat local

investment not as an environmentally neutral variable, but as a structural channel through which development affects emissions (Oncu et al., 2025; Trinugroho et al., 2025).

Empirical evidence generally suggests that the environmental consequences of local investment depend on its composition and the broader economic setting in which it occurs. Oncu et al. (2025) show that capital accumulation has a causal effect on CO<sub>2</sub> emissions in a cross-country panel, while Suleman et al. (2025) report that gross capital formation has both short-run and long-run relationships with CO<sub>2</sub> emissions and exerts a stronger effect in highly trade-open economies. Similarly, Trinugroho et al. (2025) find that domestic investment is positively associated with environmental degradation, implying that investment-led expansion often remains environmentally costly when it is not sufficiently green in composition. These findings support the view that domestic capital formation can intensify emissions when economic expansion is still tied to conventional technologies and carbon-intensive sectors (Suleman et al., 2025; Trinugroho et al., 2025). At the same time, the literature also indicates that local investment can support environmental sustainability under appropriate conditions. Wang et al. (2025) find that domestic gross fixed capital formation promotes sustainable development in emerging economies, especially when combined with renewable electricity generation. This suggests that the environmental effect of local investment is conditional rather than fixed: investment may worsen environmental degradation when it deepens carbon-intensive growth, but it may reduce environmental pressure when it is aligned with cleaner energy systems and sustainability-oriented development strategies. In the Saudi context, Alshammry and Muneer (2023) identify capital formation as a relevant driver of environmental degradation, which indicates that domestic investment remains an important explanatory factor in understanding CO<sub>2</sub> emissions in the Kingdom. Overall, the literature suggests that local investment should be interpreted as a context-dependent determinant whose environmental impact depends on whether capital accumulation supports green transformation or conventional emission-intensive growth (Wang et al., 2025; Alshammry & Muneer, 2023).

### **2.4 Trade openness and environmental degradation**

Trade openness is one of the most debated determinants of environmental degradation in the

empirical literature. In theory, greater openness may worsen environmental quality by expanding production, transport activity, and energy use, especially in economies where trade is tied to carbon-intensive sectors. At the same time, trade can also improve environmental outcomes by facilitating access to cleaner technologies, more efficient inputs, and better production standards. Recent evidence reflects this ambiguity. In Saudi Arabia, Aldegheishem (2024) finds that trade openness has a positive and statistically significant effect on CO<sub>2</sub> emissions in both the short and long run. By contrast, Mebrek et al. (2024) report that trade openness reduces emissions in the long run in the MENA region, while Pham and Nguyen (2024) find no statistically significant average effect of trade openness on environmental pollution in a broad sample of developing countries. Similarly, Barkat et al. (2025) show for OECD countries that trade openness has a direct positive effect on CO<sub>2</sub> emissions, but an indirect negative effect through income growth, implying that its environmental consequences are not uniform across stages of development.

More recent studies further suggest that the trade-environment nexus is nonlinear and highly context-dependent. Zhou et al. (2025) examine emerging countries and confirm that trade openness remains an important driver of carbon outcomes in economies where trade expansion is closely linked to energy demand and industrial activity. Bakri et al. (2025) identify a threshold effect in selected Asian countries, showing an inverted U-shaped relationship in which trade openness initially raises carbon emissions but begins to reduce them after a certain level is reached. In a related study, Derindag and Aldawsari (2025) find that trade openness can help mitigate carbon emissions when it is associated with cleaner technologies and energy-efficient production processes. Sakilu and Chen (2025) add further nuance by distinguishing exports from imports: in their sample of 20 developing countries, exports reduce CO<sub>2</sub> emissions, whereas imports increase them. Taken together, these findings indicate that the environmental effect of trade openness depends not only on the degree of openness itself, but also on trade composition, technological content, energy structure, and the regulatory environment.

In the Saudi context, this mixed literature is especially relevant. Saudi Arabia is a highly open and energy-intensive economy, which means that trade openness may either intensify environmental degradation through production and transport expansion or reduce it if openness accelerates cleaner

technologies and more efficient production methods. However, Saudi-specific evidence remains limited, and the available direct evidence leans toward a pollution-increasing effect. This justifies including trade openness in the present model as an important control variable for explaining CO<sub>2</sub> emissions in the Kingdom.

### **2.5 Urbanization and environmental degradation**

Urbanization is widely recognized as an important determinant of environmental degradation, although its effect is not always linear. In theory, rapid urbanization may increase CO<sub>2</sub> emissions by raising energy demand, transport intensity, housing expansion, construction activity, and pressure on urban infrastructure. Recent evidence from the Gulf and comparable economies generally supports this concern. Amer et al. (2025) show that urbanization contributes to higher carbon emissions in GCC countries, although its squared term suggests that environmental efficiency may improve at more advanced stages of urban development. In a related country-specific study, Adela et al. (2025) find that urbanization increases carbon emissions in the United Arab Emirates, while Tunio et al. (2025) report that urbanization is a significant long-run driver of ecological degradation in high-income economies. For the MENA region, Mahmood and Furqan (2025) likewise find that urbanization increases emissions, even though the renewable-energy transition helps mitigate this effect. These studies suggest that urban growth often worsens environmental pressure when it is accompanied by fossil-fuel dependence and energy-intensive development patterns.

At the same time, more recent research indicates that urbanization can also improve environmental outcomes under certain conditions. Ma and Ogata (2024), using data from 136 countries and regions, find an overall negative relationship between urbanization and CO<sub>2</sub> emissions, with the effect being especially evident in non-OECD countries. Similarly, Qiao et al. (2025) show that urbanization can improve carbon-emission performance through agglomeration effects and better land-use efficiency, even though excessive land development may still generate negative environmental externalities. Bashayreh et al. (2024) also report a nonlinear relationship in Jordan: urbanization initially raises CO<sub>2</sub> emissions, then reduces them when renewable electricity penetration becomes sufficiently strong, and later turns positive again. Together, these findings imply that the environmental effect of urbanization depends on urban form, land-use

efficiency, infrastructure quality, and the energy system supporting urban expansion.

A further strand of the literature emphasizes that the environmental consequences of urbanization are spatially heterogeneous rather than uniform. Zhang et al. (2025) show that the impact of urbanization on anthropogenic CO<sub>2</sub> emissions varies significantly across urban clusters, land-use patterns, and local climate zones, with urban morphology playing a central role in shaping emission intensity. This spatial perspective is particularly relevant for Saudi Arabia, where rapid urban development, large metropolitan concentration, and infrastructure-intensive growth may generate different environmental effects across cities and sectors. Overall, the literature suggests that urbanization should be treated as a context-dependent factor: it may intensify environmental degradation when urban growth is energy-intensive and poorly planned, but it may also contribute to lower emissions when accompanied by compact planning, efficient land use, cleaner transport, and renewable-energy integration. This makes urbanization a necessary variable in the present study's model of environmental degradation in Saudi Arabia.

## 2.6 Foreign direct investment and environmental degradation

Foreign direct investment (FDI) occupies a central place in the literature on environmental degradation because it can operate through two competing channels. According to the pollution haven view, foreign capital may increase environmental degradation when multinational firms relocate pollution-intensive activities to host countries with relatively lower environmental costs. By contrast, the pollution halo perspective suggests that FDI can improve environmental quality through technology transfer, managerial know-how, and cleaner production methods. Recent Saudi evidence reflects this ambiguity. Elimam and Alattas (2025) report that positive FDI growth is associated with higher CO<sub>2</sub> emissions in Saudi Arabia, implying that foreign capital can aggravate environmental pressure when it is tied to emission-intensive activity. In contrast, Haseeb et al. (2026) find that, in Saudi Arabia, FDI is associated with long-run environmental benefits when analyzed alongside eco-innovation, financial development, and clean energy. These contrasting findings suggest that the environmental effect of FDI in the Kingdom depends on the composition of inflows and the broader policy and technological setting.

The broader empirical literature likewise shows that the FDI-environment nexus is mixed but often leans toward a pollution-increasing effect in developing and emerging economies. Pham et al. (2025) provide new global evidence that FDI inflows significantly increase CO<sub>2</sub> emissions, both in total quantity and intensity, with low- and middle-income countries being disproportionately affected. Similarly, Kutlu Furtuna and Atis (2024), focusing on the largest carbon-intensive countries, identify a U-shaped relationship in which FDI initially reduces carbon emissions up to a threshold and then increases environmental degradation beyond that point. In Asia, Nguyen et al. (2025) show that while FDI supports economic growth, CO<sub>2</sub> emissions mediate this relationship, indicating that part of the growth effect may come with environmental costs. Tripathy et al. (2025) reach a related conclusion for India, showing that FDI affects CO<sub>2</sub> emissions mainly through mediating channels such as energy structure, industrial structure, and high-carbon technology. Together, these studies suggest that FDI often worsens environmental degradation when it expands carbon-intensive production systems or reinforces fossil-fuel-based growth patterns.

At the same time, recent evidence also shows that FDI can support environmental sustainability under suitable institutional and energy conditions. Yu et al. (2025), using evidence from the E-7 economies, find that FDI is negatively correlated with carbon emissions and moderates the emission-enhancing effects of urbanization and human capital. Pan et al. (2025) similarly report that FDI can mitigate CO<sub>2</sub> emissions in developing countries, although its environmental role becomes more conditional when combined with renewable energy consumption and other mediating factors. This suggests that FDI is not inherently harmful or beneficial from an environmental perspective. Rather, its impact depends on whether foreign capital is directed toward cleaner technologies, renewable energy, and efficient production, or instead toward conventional carbon-intensive sectors. Overall, the literature indicates that FDI should be treated as a context-dependent determinant of environmental degradation, which justifies its inclusion in the present Saudi model.

## 2.7 Digitalization evidence in the Saudi context

Empirical evidence on digitalization and environmental degradation in Saudi Arabia is still emerging, but recent studies indicate that digital variables are increasingly relevant to the Kingdom's environmental and sustainability trajectory. Existing

Saudi research does not rely on a single measure of digital transformation; instead, it uses a range of proxies such as ICT diffusion, internet use, technological integration, digital innovation, and sectoral digital adoption. This methodological diversity reflects the evolving nature of the literature and suggests that digitalization may influence environmental outcomes through several channels, including efficiency improvement, cleaner production, and renewable-energy integration (Bennaceur et al., 2024; Abid & Gafsi, 2025; Khan et al., 2026).

Several recent Saudi studies provide evidence that digitalization can mitigate environmental pressure. Bennaceur et al. (2024) find that ICT diffusion reduces CO<sub>2</sub> emissions in the long run, particularly when combined with renewable energy consumption. Sadaoui et al. (2025) likewise report that ICT diffusion reduces environmental degradation in Saudi Arabia, although its moderating effect on the informal economy-pollution nexus becomes stronger only after a threshold level of ICT is reached. More recently, Abid et al. (2026) show that ICT and financial development jointly improve environmental sustainability in Saudi Arabia, with internet use and fixed subscriptions contributing positively, whereas mobile subscriptions appear to worsen sustainability outcomes. These studies collectively suggest that digitalization can support lower emissions and better environmental performance, but that its effectiveness depends on supportive financial and energy conditions

At the same time, Saudi evidence shows that the environmental benefits of digitalization are highly dependent on the form and setting of digital adoption. Abid and Gafsi (2025) show that technological integration is closely linked to environmental sustainability in Saudi Arabia, emphasizing that technology-related upgrading influences long-term ecological outcomes. At the sectoral level, Alsuhaibany (2025) finds that digital innovation significantly improves sustainability in the Saudi oil and gas sector by enhancing operational efficiency, reducing waste, and supporting circular-economy practices. However, other Saudi evidence suggests that digital technologies alone are not sufficient to deliver sustainability gains unless they are supported by organizational readiness and effective implementation. More broadly, Khan et al. (2026) argue that Saudi Arabia has made notable progress in digital sustainability, but that long-term environmental gains still depend on regulatory coordination, infrastructure readiness, and the

integration of sustainability principles into digital strategy (Abid & Gafsi, 2025; Alsuhaibany, 2025; Khan et al., 2026).

Overall, the Saudi literature suggests that digitalization is increasingly associated with environmental sustainability, but the evidence remains proxy-specific, sector-dependent, and institutionally conditioned. Digital transformation appears to reduce environmental degradation when it is linked to renewable energy, financial support, efficiency gains, and circular-economy practices. Yet the evidence also implies that digitalization on its own does not guarantee environmental improvement. This reinforces the need for the present study, which examines whether digital transformation exerts a measurable effect on CO<sub>2</sub> emissions in Saudi Arabia within a broader macroeconomic framework (Bennaceur et al., 2024; Sadaoui et al., 2025; Abid et al., 2026; Abid & Gafsi, 2025; Khan et al., 2026).

The literature shows that environmental degradation in Saudi Arabia is shaped by a combination of structural, investment, trade, and technological forces. However, three gaps remain evident. First, most Saudi studies still focus on conventional drivers such as energy use, growth, trade, and urbanization, while digital transformation remains comparatively underexplored. Second, the Saudi digitalization literature has relied mainly on ICT or internet-use proxies, which leaves room for broader measures of digital transformation in empirical analysis. Third, relatively few Saudi studies appear to examine digital transformation, local investment, trade openness, urbanization, and foreign direct investment together within a single framework using CO<sub>2</sub> emissions as the environmental outcome. The present study addresses this gap by integrating these variables into one Saudi-specific model, thereby offering a more comprehensive explanation of how economic modernization and digital change interact with environmental degradation in the Kingdom.

### 3. Data, Variables, and Model Specification

#### 3.1 Data and study coverage

This study employs annual time-series data for the Kingdom of Saudi Arabia covering the period 1990–2024. The data are drawn primarily from the World Development Indicators (WDI) database for the macroeconomic and environmental variables used in the analysis, while the Digital Economy and Society Index (DESI) is used as the proxy for digital transformation. The use of annual data is appropriate because the study investigates long-run structural relationships among environmental degradation,

digital transformation, trade openness, urbanization, local investment, and foreign direct investment in Saudi Arabia.

The selected period is appropriate because it captures important phases in Saudi Arabia's economic transformation, including increasing trade integration, rising urbanization, changing investment patterns, and the growing relevance of digitalization in the economy. The study focuses on environmental degradation at the national level, using CO<sub>2</sub> emissions (metric tons per capita) as the dependent variable. The explanatory variables include digital transformation, trade openness, urbanization, gross capital formation, and foreign direct investment, which together provide a comprehensive framework for examining the determinants of environmental degradation in Saudi Arabia.

### 3.2 Variable description and measurement

- Environmental degradation, proxied by CO<sub>2</sub> emissions (metric tons per capita), is the dependent variable in this study. This variable is widely used in empirical environmental research because it directly captures the carbon intensity associated with economic activity, energy use, transport expansion, and production processes. In the context of Saudi Arabia, CO<sub>2</sub> emissions provide a relevant indicator of the environmental consequences of growth and structural transformation. The independent variables are:

- Digital transformation is measured by the Digital Economy and Society Index (DESI). This variable is used to capture the level of digital advancement in the economy, including the expansion of digital infrastructure, technological integration, and broader digital readiness. A rise in digital transformation may reduce environmental degradation through efficiency gains, smart systems, and improved resource allocation. However, it may also increase emissions if digital expansion raises electricity demand, data-processing intensity, and technology-related consumption. Therefore, the expected effect of digital transformation on CO<sub>2</sub> emissions is theoretically ambiguous.

- Trade openness is measured by trade as a percentage of GDP. This variable reflects the extent to which the Saudi economy is integrated into international markets. Trade may improve environmental quality if it facilitates access to cleaner technologies and more efficient production inputs. Conversely, it may worsen environmental degradation by expanding transport activity, industrial output, and energy-intensive trade-related

production. The expected sign is therefore mixed, although a positive effect on emissions is often expected in carbon-intensive economies.

- Urbanization is proxied by urban population as a percentage of total population. This variable captures the degree of population concentration in urban areas. Urbanization may increase emissions through construction activity, transport demand, energy consumption, and pressure on infrastructure. At the same time, it may support more efficient service delivery, better infrastructure use, and technological innovation. In developing and rapidly transforming economies, however, the effect is often expected to be positive, implying higher environmental degradation.

- Local investment is represented by gross capital formation as a percentage of GDP. This variable is used as a proxy for domestic investment and reflects the level of capital accumulation in the economy. Its effect on environmental degradation depends on the composition of investment. If capital formation is directed toward cleaner technologies and sustainable infrastructure, it may reduce emissions. If it is concentrated in construction, industry, and carbon-intensive sectors, it may increase CO<sub>2</sub> emissions. Thus, the expected sign remains theoretically open, although a positive association is plausible in the absence of strong green investment orientation.

- Foreign direct investment is measured by FDI net inflows as a percentage of GDP. This variable captures the role of foreign capital in shaping production structure and economic activity. FDI may reduce emissions through technology transfer and cleaner managerial practices, but it may also increase emissions when inflows are directed toward pollution-intensive sectors. Accordingly, its effect on environmental degradation may be either positive or negative depending on the nature of foreign investment.

### 3.3. Empirical model specification

To examine the relationship between digital transformation, local investment, and environmental degradation in Saudi Arabia, the study specifies the following empirical model:

$$CO_2t = \beta_0 + \beta_1 DESI_t + \beta_2 TRADE_t + \beta_3 URB_t + \beta_4 GCF_t + \beta_5 FDI_t + \varepsilon_t$$

where:

- CO<sub>2t</sub>: denotes carbon dioxide emissions per capita at time t,
- DESI<sub>t</sub>: represents digital transformation,
- TRADE<sub>t</sub>: captures trade openness,
- URB<sub>t</sub>: denotes urbanization,

- GCF<sub>t</sub>: represents gross capital formation as a proxy for local investment,
- FDI<sub>t</sub>: captures foreign direct investment net inflows, and
- ε<sub>t</sub>: is the stochastic error term.

To improve interpretability and reduce potential heteroskedasticity, the dependent variable may be expressed in logarithmic form, provided that the data properties support such a transformation. In that case, the model can be written as:

$$\ln \text{CO2}_t = \beta_0 + \beta_1 \text{DESI}_t + \beta_2 \text{TRADE}_t + \beta_3 \text{URB}_t + \beta_4 \text{GCF}_t + \beta_5 \text{FDI}_t + \varepsilon_t$$

This semi-log specification is particularly useful because it allows the coefficients to be interpreted in terms of the effect of each explanatory variable on environmental degradation while preserving the level form of variables expressed as percentages or indices.

Since FDI may take negative values in some years, the conventional natural-log transformation is not appropriate for this variable. To retain all observations while reducing scale asymmetry, the study uses the log-modulus transformation, defined as:

$$\text{LM}(X_t) = \text{sign}(X_t) \ln(1 + |X_t|)$$

Accordingly, the empirical model is estimated as:

$$\ln \text{CO2}_t = \beta_0 + \beta_1 \text{DESI}_t + \beta_2 \text{TRADE}_t + \beta_3 \text{URB}_t + \beta_4 \text{GCF}_t + \beta_5 \text{LM}(\text{FDI}_t) + \varepsilon_t$$

## 4. ECONOMETRIC METHODOLOGY

### 4.1 Preliminary unit root tests

Before estimating the long-run and short-run relationships among the variables, it is necessary to examine their order of integration. This study, therefore, begins by applying conventional unit root tests to determine whether the series are stationary at level, first difference, or both. In particular, the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test are employed. These tests are widely used in time-series analysis to identify the stationarity properties of the variables and to ensure that none of the series is integrated of order two,  $I(2)$ , since the ARDL bounds-testing approach is valid only when the variables are integrated of order zero,  $I(0)$ , order one,  $I(1)$ , or a combination of both.

The unit root analysis is important because non-stationary variables may produce spurious regression results if their time-series properties are ignored. Accordingly, the study first tests each variable in level form and then in first differences where necessary. Once the integration properties are identified, the appropriate econometric framework can be selected for examining the existence of a long-run equilibrium relationship among the variables.

### 4.2 ARDL model specification

To investigate the relationship between digital transformation, local investment, and environmental degradation in Saudi Arabia, this study adopts the Autoregressive Distributed Lag (ARDL) approach. The ARDL technique is appropriate for this study for several reasons. First, it can be applied when the variables are integrated of mixed order, provided that none is  $I(2)$ . Second, it performs well in small samples, which is suitable for the annual dataset covering 1990–2024. Third, it allows the estimation of both long-run and short-run dynamics within a unified framework.

The general ARDL model corresponding to the study variables can be expressed as follows:

$$\text{CO2}_t = \alpha_0 + \sum_{i=1}^p \alpha_1 \text{CO2}_{t-i} + \sum_{i=0}^{q1} \alpha_2 \text{DESI}_{t-i} + \sum_{i=0}^{q2} \alpha_3 \text{TRADE}_{t-i} + \sum_{i=0}^{q3} \alpha_4 \text{URB}_{t-i} + \sum_{i=0}^{q4} \alpha_5 \text{GCF}_{t-i} + \sum_{i=0}^{q5} \alpha_6 \text{FDI}_{t-i} + \varepsilon_t$$

The optimal lag structure of the ARDL model is selected using an information criterion such as the Akaike Information Criterion (AIC). The use of an optimal lag structure is necessary to avoid over-parameterization and to ensure that the dynamic specification adequately captures the variables' behavior over time.

### 4.3 ARDL bounds test for cointegration

After establishing the order of integration of the variables, the study applies the ARDL bounds-testing procedure to determine whether a long-run cointegration relationship exists among the variables. The unrestricted error correction representation of the ARDL model can be written as follows:

$$\Delta \text{CO2}_t = \beta_0 + \sum_{i=1}^p \beta_1 \Delta \text{CO2}_{t-i} + \sum_{i=0}^{q1} \beta_2 \Delta \text{DESI}_{t-i} + \sum_{i=0}^{q2} \beta_3 \Delta \text{TRADE}_{t-i} + \sum_{i=0}^{q3} \beta_4 \Delta \text{URB}_{t-i} + \sum_{i=0}^{q4} \beta_5 \Delta \text{GCF}_{t-i} + \sum_{i=0}^{q5} \beta_6 \Delta \text{FDI}_{t-i} + \lambda_1 \text{CO2}_{t-1} + \lambda_2 \text{DESI}_{t-1} + \lambda_3 \text{TRADE}_{t-1} + \lambda_4 \text{URB}_{t-1} + \lambda_5 \text{GCF}_{t-1} + \lambda_6 \text{FDI}_{t-1} + u_t$$

The null hypothesis of no cointegration is stated as:

$$H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \lambda_6 = 0$$

against the alternative hypothesis:

$$H_1: \lambda_1 \neq 0, \lambda_2 \neq 0, \lambda_3 \neq 0, \lambda_4 \neq 0, \lambda_5 \neq 0, \lambda_6 \neq 0$$

The decision is based on the computed F-statistic. If the F-statistic exceeds the upper critical bound, the null hypothesis of no long-run relationship is rejected, confirming cointegration. If it falls below the lower bound, the null cannot be rejected. If it lies between the two bounds, the result is inconclusive.

### 4.4 Estimation of long-run and short-run dynamics

Once cointegration is confirmed, the ARDL model is used to estimate the long-run coefficients of the explanatory variables. These coefficients show the long-

term effect of digital transformation, trade openness, urbanization, gross capital formation, and foreign direct investment on CO2 emissions in Saudi Arabia.

To capture short-run adjustments, the study estimates the associated error correction model (ECM). The ECM specification can be expressed as:

$$\Delta\text{CO2}_t = \gamma_0 + \sum_{i=1}^p \gamma_1 \Delta\text{CO2}_{t-i} + \sum_{i=0}^{q1} \gamma_2 \Delta\text{DESI}_{t-i} + \sum_{i=0}^{q2} \gamma_3 \Delta\text{TRADE}_{t-i} + \sum_{i=0}^{q3} \gamma_4 \Delta\text{URB}_{t-i} + \sum_{i=0}^{q4} \gamma_5 \Delta\text{GCF}_{t-i} + \sum_{i=0}^{q5} \gamma_6 \Delta\text{FDI}_{t-i} + \phi\text{ECM}_{t-i} + \mu_t$$

where  $(\text{ECM}_{t-i})$  is the lagged error correction term derived from the long-run relationship. The coefficient of the error correction term  $(\phi)$  is expected to be negative and statistically significant. This coefficient measures the speed at which short-run deviations from long-run equilibrium are corrected. A negative and significant error correction term confirms the existence of a stable long-run relationship and indicates how quickly the system returns to equilibrium after a short-run shock.

#### 4.5 Diagnostic and stability tests

To ensure the reliability and robustness of the estimated ARDL model, several post-estimation diagnostic tests are conducted. First, the Breusch–Godfrey serial correlation LM test is used to check whether the residuals are free from autocorrelation. Second, the Breusch–Pagan–Godfrey test is used to assess the presence of heteroskedasticity. Third, the Jarque–Bera test is used to assess whether the residuals are normally distributed. Fourth, the Ramsey RESET test is applied to verify the functional form of the model.

In addition to these diagnostic checks, the stability of the estimated coefficients is examined using the CUSUM and CUSUM of Squares (CUSUMSQ) tests. These tests are important because they indicate

whether the estimated model remains stable over the sample period. If the plots remain within the critical bounds, the model is considered structurally stable.

Thus, the empirical analysis proceeds through several stages. First, the study examines the stationarity properties of the variables using ADF and PP unit root tests. Second, the ARDL model is estimated using an optimal lag structure selected by an information criterion. Third, the bounds test is applied to determine whether a long-run cointegration relationship exists among the variables. Fourth, once cointegration is established, the long-run coefficients and short-run error correction dynamics are estimated. Finally, diagnostic and stability tests are performed to confirm the adequacy and robustness of the estimated model.

## 5. RESULTS

### 5.1. descriptive statistics

The descriptive statistics show that all variables have 35 observations, indicating a balanced annual dataset. LN\_CO2 has the highest mean value (5.923), followed by LN\_URB (4.398) and LN\_TRADE (4.220), while LM\_FDI records the lowest mean (0.426) and the highest variability, as reflected by its standard deviation (0.601). LN\_DESI also shows relatively high dispersion, suggesting noticeable changes in digitalization over the study period. The skewness values are generally negative for most variables, indicating slight left-skewed distributions, while kurtosis values are below 3, suggesting flatter distributions than the normal distribution. The Jarque–Bera probability values are all above 0.05, meaning the null hypothesis of normality cannot be rejected; therefore, the variables are approximately normally distributed.

Table 1: Descriptive statistics of the variables

	LN_CO2	LM_FDI	LN_DESI	LN_GCF	LN_TRADE	LN_URB
Mean	5.923	0.426	2.446	3.163	4.220	4.398
Median	5.961	0.453	2.626	3.149	4.206	4.400
Maximum	6.481	1.432	3.558	3.479	4.565	4.445
Minimum	5.158	-0.836	0.000	2.753	3.861	4.338
Std. Dev.	0.444	0.601	1.092	0.181	0.181	0.029
Skewness	-0.255	-0.230	-0.791	-0.102	0.105	-0.194
Kurtosis	1.571	2.213	2.746	2.124	2.144	2.015
Jarque-Bera	3.359	1.213	3.748	1.180	1.134	1.633
Probability	0.187	0.545	0.154	0.554	0.567	0.442
Sum	207.318	14.914	85.609	110.699	147.713	153.939
Sum Sq. Dev.	6.688	12.295	40.528	1.113	1.118	0.029
Observations	35	35	35	35	35	35

### 5.2. Unit-root Test

The unit root results indicate a mixed order of integration among the variables. At the level form, LN\_CO2, LN\_DESI, LN\_GCF, and LN\_TRADE are

non-stationary because their probability values are greater than 0.05; however, after first differencing, they become stationary, meaning they are integrated of order one, I(1). In contrast, LN\_URB and LM\_FDI are

stationary at level because their probability values are below 0.05, meaning they are integrated of order zero, I(0). Therefore, the variables are a combination of I(0)

and I(1), and none appears to be I(2), which supports the suitability of the ARDL bounds testing approach for examining long-run and short-run relationships.

Table 2. Unit-root Test EViews outcome

Variable	Test	Level			First Difference		
		Statistic	Prob	Conclusion	Statistic	Prob	Conclusion
LN_CO2	ADF	-1.891008	0.6358	Non-stationary	-4.684711	0.0035	Stationary
LN_DESI	ADF	-0.527795	0.9771	Non-stationary	-6.072141	0.0001	Stationary
LN_GCF	ADF	-2.897242	0.1759	Non-stationary	-5.447433	0.0005	Stationary
LN_TRADE	PP	-1.241673	0.6447	Non-stationary	-4.633367	0.0008	Stationary
LN_URB	PP	-17.46018	0.0000	Stationary			
LM_FDI	ADF	-4.868219	0.0021	Stationary			

### 5.3. VAR Lag length Criteria

The VAR lag order selection results suggest that lag 2 is the optimal lag length for the model. This is because all major criteria – LR, FPE, AIC, SC, and HQ – select lag 2, as indicated by the asterisks. Specifically, lag 2 provides the lowest values for the information criteria and final

prediction error, implying better model fit and forecasting performance compared with lag 0 and lag 1. Therefore, using two lags is appropriate for the subsequent ARDL or VAR-based estimations, as it captures the dynamic relationships among the variables while maintaining model efficiency.

Table 3. VAR Lag length Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	93.0694	NA	2.06e-10	-5.276936	-5.004844	-5.185385
1	312.7117	346.1029	3.14e-15	-16.40677	-14.50212	-15.76591
2	378.6155	79.88339*	6.46e-16*	-18.21912*	-14.68192*	-17.02896*

\* Indicates lag order selected by the criterion

### 5.4. ARDL Bound Test

The ARDL Bounds Test results provide evidence of a long-run cointegration relationship among the variables. The calculated F-statistic (4.1979) exceeds the upper critical bound I(1) at the 10% level (3.00), 5% level (3.38), and 2.5% level (3.73), and is also slightly above the 1% upper bound (4.15). Since the

F-statistic is greater than the upper bound critical values, the null hypothesis of no levels relationship is rejected. This confirms the existence of a stable long-run equilibrium relationship between the dependent variable and the explanatory variables, supporting the use of the ARDL long-run and error correction estimations.

Table 4: long-run ARDL bound test

Test Statistic	Value	Signific-	I(0)	I(1)
Asymptotic n=1000				
F-statistic	4.19789	10%	2.08	3
k	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15

### 5.5. Error Correction Model (ECM)

The ARDL-ECM results show that the model explains about 81% of short-run changes in CO<sub>2</sub> emissions. The error correction term is negative and highly significant, confirming a stable long-run relationship. Its coefficient -0.242 means that about 24.2% of disequilibrium is corrected each year. Lagged CO<sub>2</sub> emissions have a significant negative

effect, indicating short-run adjustment dynamics. FDI is weakly negative in the current period but becomes positive and significant after one lag. Gross capital formation has a positive and significant effect on CO<sub>2</sub> emissions. Urbanization is insignificant, suggesting no clear short-run impact. Thus, the results confirm gradual adjustment toward long-run equilibrium.

Table 5. ARDL-ECM results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LN_CO2(-1))	-0.365048	0.114539	-3.187099	0.0049
D(LM_FDI)	-0.007771	0.004326	-1.796332	0.0884

D(LM_FDI(-1))	0.024989	0.004668	5.353222	0
D(LN_GCF)	0.113352	0.028877	3.925348	0.0009
D(LN_GCF(-1))	0.058749	0.026117	2.249453	0.0365
D(LN_URB)	4.83276	4.636283	1.042378	0.3103
D(LN_URB(-1))	-7.039271	4.265742	-1.650187	0.1153
CointEq(-1)*	-0.242339	0.028876	-8.392538	0
R-squared	0.810101	Mean dependent var		0.039429
Adjusted R-squared	0.756929	S.D. dependent var		0.03118
S.E. of regression	0.015373	Akaike info criterion		-5.305242
Sum squared resid	0.005908	Schwarz criterion		-4.942452
Log likelihood	95.53649	Hannan-Quinn criter.		-5.183174
Durbin-Watson stat	2.247061			

### 5.6. Diagnostic tests of the model

The diagnostic tests generally support the adequacy of the ARDL model. The Breusch–Godfrey LM test shows no serious serial correlation based on the F-statistic probability 0.6273, although the Chi-square result is significant and should be noted cautiously. The Breusch–Pagan–Godfrey test confirms homoscedasticity, since all probabilities are above 0.05. The Jarque–Bera probability 0.4875 indicates

that the residuals are normally distributed. The Ramsey RESET test is insignificant based on the t- and F-statistics 0.4789, suggesting no major functional form misspecification, although the likelihood ratio result is significant. Overall, the model passes most key diagnostic checks, but the mixed LM and RESET results should be acknowledged as a limitation.

**Table 6.** Diagnostic tests results

Test	Statistic	Value	Probability Label	Prob
Breusch–Godfrey LM	F-statistic	0.770515	Prob. F(2,1)	0.6273
	Obs*R-squared	18.80023	Prob. Chi-Square(2)	0.0001
Breusch–Pagan–Godfrey	F-statistic	0.334445	Prob. F(25,5)	0.9701
	Obs*R-squared	19.39917	Prob. Chi-Square(25)	0.7776
	Scaled explained SS	0.21703	Prob. Chi-Square(25)	1
Ramsey RESET	t-statistic	0.86335	2	0.4789
	F-statistic	0.745374	(1,2)	0.4789
	Likelihood ratio	9.819869	1	0.0017
Normality	Jarque-Bera	1.436959		0.487493
	Mean	6.74E-14		
	Std. Dev.	0.002648		
	Skewness	0.49016		
	Kurtosis	3.389176		

## 6. DISCUSSION OF THE FINDINGS

This paper aims to examine how digital transformation, local investment, trade openness, urbanization, and foreign direct investment affect environmental degradation in Saudi Arabia. The empirical results confirm a stable long-run relationship between CO2 emissions and the selected explanatory variables in Saudi Arabia. The ARDL bounds test supports cointegration, while the negative and highly significant error-correction term indicates that short-run deviations converge gradually to long-run equilibrium, with nearly 24.2% of disequilibrium corrected each year. This suggests that environmental degradation in Saudi Arabia is shaped by persistent macro-structural forces rather than by temporary shocks alone, which is consistent with recent Saudi evidence linking emissions to long-run growth, energy use, and structural

transformation (Tahir et al., 2024; Khan & Khan, 2024; Tlili et al., 2025).

A key finding is that gross capital formation exerts a positive and significant effect on CO2 emissions in the short run. This indicates that local investment in Saudi Arabia has mainly been associated with infrastructure expansion, construction, and other energy-intensive activities rather than with green transformation. This result is in line with Alshammry and Muneer (2023), who also find that capital formation contributes to environmental degradation in Saudi Arabia, and with broader recent evidence showing that domestic investment can intensify emissions when it is concentrated in conventional sectors (Oncu et al., 2025; Trinugroho et al., 2025; Suleman et al., 2025). However, it contrasts with Wang et al. (2025), who show that domestic investment may improve environmental sustainability when combined with renewable

electricity and cleaner structural change. The implication is that the environmental effect of local investment depends critically on the composition and quality of capital accumulation.

The results for foreign direct investment are more nuanced. While the contemporaneous coefficient is weakly negative, the lagged FDI effect is positive and highly significant, implying that foreign capital does not immediately raise emissions but becomes environmentally costly after investment projects become operational. This pattern is consistent with the view that FDI may initially enter through financing and project preparation, but later increases production, transport activity, and energy demand. The finding supports recent Saudi and international evidence that FDI often worsens environmental quality when it supports carbon-intensive activities (Elimam & Alattas, 2025; Pham et al., 2025; Tripathy et al., 2025). At the same time, it differs from studies showing that FDI can improve sustainability when combined with eco-innovation, clean energy, and stronger institutions (Haseeb et al., 2026; Yu et al., 2025; Pan et al., 2025). Thus, the present results suggest that the environmental impact of FDI in Saudi Arabia remains conditional on the sectoral destination and technological content of inflows.

Urbanization, by contrast, does not show a statistically significant short-run effect on CO<sub>2</sub> emissions. This may reflect the already high and relatively stable degree of urbanization in Saudi Arabia, as well as the possibility that urbanization affects emissions indirectly through infrastructure, transport systems, and energy use rather than through immediate annual changes. This result does not necessarily contradict the wider literature, since recent studies show that urbanization may either worsen or improve environmental outcomes depending on urban form, agglomeration efficiency, renewable-energy penetration, and planning quality (Amer et al., 2025; Ma & Ogata, 2024; Bashayreh et al., 2024; Zhang et al., 2025). Overall, the findings indicate that environmental degradation in Saudi Arabia is closely tied to the structure of domestic investment and foreign capital inflows, while adjustment toward equilibrium remains gradual. These results reinforce the need to align both local and foreign investment with cleaner technologies, energy-efficient infrastructure, and broader sustainability objectives.

## 6. CONCLUSION

This study examined the effects of digital transformation, local investment, trade openness, urbanization, and foreign direct investment on

environmental degradation in the Kingdom of Saudi Arabia over the period 1990–2024. Using CO<sub>2</sub> emissions per capita as a proxy for environmental degradation and applying the ARDL approach, the results confirmed the existence of a stable long-run relationship among the variables. The error-correction term was negative and highly significant, indicating that short-run disequilibrium adjusts gradually toward long-run equilibrium.

The empirical findings show that gross capital formation increases CO<sub>2</sub> emissions in the short run, suggesting that domestic investment has largely been associated with energy-intensive expansion rather than green transformation. Foreign direct investment displayed a mixed short-run pattern, with a weak negative contemporaneous effect but a positive and significant lagged effect, implying that its environmental cost becomes more visible after investment projects become operational. Urbanization, on the other hand, did not exert a statistically significant short-run effect, indicating that its environmental influence may be more gradual or may operate indirectly through other structural channels. Overall, the results suggest that environmental degradation in Saudi Arabia remains closely linked to the structure and composition of investment-led development.

These findings carry important policy implications. First, domestic investment should be redirected toward cleaner infrastructure, energy-efficient production, and environmentally sustainable technologies. Second, foreign investment policies should place greater emphasis on sectoral quality, so that FDI is attracted into low-carbon and innovation-driven activities rather than pollution-intensive sectors. Third, environmental sustainability should be more deeply integrated into the broader process of economic modernization, especially as Saudi Arabia continues to expand its digital and investment base. In this respect, the transition toward greener growth requires not only more investment, but also better-targeted investment supported by environmental regulation and technological upgrading.

Despite its contributions, the study has some limitations. The analysis is based on annual time-series data for a single country, which may limit the generalizability of the findings. In addition, the environmental effect of digital transformation may depend on the proxy used and on sector-specific conditions that are not fully captured in aggregate data. Future research may extend this work by incorporating alternative digitalization measures, sector-level evidence, structural break analysis, or

comparative studies across GCC countries. Such extensions would provide a deeper understanding of how technological and investment dynamics interact with environmental sustainability in rapidly transforming economies.

### 6.1 Policy recommendations

Based on the empirical findings, several policy recommendations emerge. First, domestic investment policy in Saudi Arabia should place greater emphasis on green capital formation by directing more resources toward renewable energy, energy-efficient infrastructure, sustainable transport, and low-carbon production technologies. Since gross capital formation was found to increase CO<sub>2</sub> emissions, the environmental quality of investment appears to matter more than the volume of investment alone. Second, foreign direct investment policy should become more selective by encouraging inflows into cleaner and innovation-driven sectors while discouraging investment in pollution-intensive activities. The positive lagged effect of FDI on emissions suggests that foreign capital may become environmentally costly once projects become fully operational, which underscores the need for stronger environmental screening and performance standards. Third, digital transformation strategies should be integrated with sustainability objectives so that digital expansion supports energy efficiency, smart monitoring, and cleaner production rather than adding to electricity demand and carbon intensity. More broadly, environmental considerations should be embedded into Saudi Arabia's broader modernization agenda through stricter regulation, greener industrial policy, and stronger alignment between investment promotion and environmental sustainability goals.

### 6.2 Study limitations

This study has several limitations that should be acknowledged. First, the analysis is based on annual time-series data for a single country, which limits the generalizability of the findings to other national contexts. Second, the sample size is relatively small, covering 1990–2024, which is common in macro time-series studies but still constrains the depth of inference. Third, environmental degradation is measured only by CO<sub>2</sub> emissions per capita, which may not fully capture other dimensions of environmental pressure, such as ecological footprint, total greenhouse gas emissions, or consumption-based emissions. Fourth, digital transformation is represented by a single aggregate proxy, which may not reflect the different environmental effects of

distinct forms of digitalization, such as internet diffusion, digital infrastructure, e-government, or industrial digitalization. Finally, although the ARDL model captures long-run and short-run dynamics, it does not fully account for possible structural breaks, asymmetric relationships, or sector-specific transmission mechanisms that may shape environmental outcomes in Saudi Arabia.

### 6.3 Future research directions

Future research can extend this study in several important ways. First, future studies may use alternative indicators of environmental degradation, such as ecological footprint, total CO<sub>2</sub> emissions, carbon intensity, or greenhouse gas emissions excluding Land Use, Land-Use Change, and Forestry (LULUCF), to test the robustness of the findings. Second, further research may employ alternative measures of digital transformation, including ICT diffusion, internet usage, digital adoption, or sector-level digitalization indicators, in order to capture the multidimensional nature of digital change more accurately. Third, future work may examine whether the effects of investment and digitalization are asymmetric or nonlinear by applying models such as NARDL or threshold techniques. Fourth, sectoral studies focusing on transport, construction, manufacturing, or energy could provide deeper insight into the channels through which domestic and foreign investment affect environmental degradation. Finally, comparative studies across GCC or MENA countries may help determine whether the Saudi findings are country-specific or part of a broader regional pattern of interaction between digital transformation, investment, and environmental sustainability.

### FUNDING

This work was supported and funded by the Deanship of Scientific Research at the University of Tabuk. (Grant number S - 0266-2024)

### ACKNOWLEDGMENTS

The authors extend their appreciation to the Deanship of Scientific Research, University of Tabuk, Saudi Arabia, for funding this work.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare there are no conflicts of interest.

## REFERENCES

2. Tahir, M., Alfalih, A. A., Osama, A. J., Azid, T., & Burki, U. (2024). Economic determinants of environmental degradation: A time series analysis of Saudi Arabian economy.
3. DOI: 10.1016/j.envc.2024.100941
4. Khan, U., & Khan, A. M. (2024). The Impact of Energy Consumption and Economic Growth on the Saudi Arabia's Carbon Emissions. DOI: 10.32479/ijeeep.15285
5. Dalia Kamal Alnagar, Abu Elgasim Abbas Abow Mohammed, Hussein Eledum, Sara Mohamed Ahmed Alsheikh, Elfarazdag M. M. Hussein, Rahmtalla Y. Yagoub, Walla Awad Maruod, Time Series Decomposition and LSTM Neural Networks for Forecasting Transportation CO2 Emissions in Saudi Arabia: Supporting Vision 2030 Climate Objectives, *Int. J. Anal. Appl.*, 24 (2026), 18. <https://doi.org/10.28924/2291-8639-24-2026-18>
6. Tlili, H., Alhamad, S., & Turki, H. (2025). How growth, urbanization, and energy consumption affect CO2 emissions in Saudi Arabia (1970–2020)? An ARDL and NARDL approach to investigate the eco-environmental challenge. DOI: 10.1016/j.esr.2025.101691
7. Binsuwadan, J., Alotaibi, L., & Almugren, H. (2025). The Role of Agriculture in Shaping CO2 in Saudi Arabia: A Comprehensive Analysis of Economic and Environmental Factors. DOI: 10.3390/su17104346
8. Ben-Ahmed, K., Melebar, S. J., & Bawazir, T. K. (2025). Environmental Degradation, Renewable Energy, and Non-Renewable Energy Consumption in Saudi Arabia: An ARDL Bound Testing Approach. DOI: 10.3390/su17114970
9. Omar, N., Klose, J., & Yousri, D. (2025). The response of CO2 emissions to macroeconomic shocks: A panel VAR analysis. DOI: 10.1016/j.dsef.2025.100102
10. Benzerrouk, Z. S., Abid, M., Ghandri, M., Hamed, N., & Adam, F. A. A. (2026). Examining the Impact of Economic Globalization on Environmental Degradation in Saudi Arabia. DOI: 10.32479/ijeeep.22517
11. Li, X., Huang, J., & Zhang, H. (2025). Digital economic development and carbon emissions: A literature review. *China Journal of Public Relations*? [publisher page lists DOI and authors]. DOI: 10.1016/j.cjpre.2025.07.007.
12. Lyu, Y., Zhang, J., Wang, W., Li, Y., & Geng, Y. (2024). Toward low carbon development through digital economy: A new perspective of factor market distortion. *Technological Forecasting and Social Change*, 208, 123685. DOI: 10.1016/j.techfore.2024.123685.
13. Xia, Y., Wu, Y., Qin, Y., & Fu, C. (2025). Mechanism and spatial spillover effect of the digital economy on carbon emission efficiency in Chinese provinces. *Scientific Reports*, 15, 19025. DOI: 10.1038/s41598-025-02184-8.
14. Wang, Q., & Gao, G. (2025). Impact of digital economy on carbon emission efficiency: Evidence from a quasi-natural experiment in "Broadband China" pilot cities. *Sustainable Futures*. DOI: 10.1016/j.sftr.2025.101025.
15. Akdemir Ömür, G., & Erkasap, A. (2025). Impact of Digitalization, Technological Innovation, and ICTs on Sustainability Management and Strategies. *Sustainability*, 17(12), 5351. DOI: 10.3390/su17125351.
16. Wang, Y., Su, Z., Cai, X., & Yu, J. (2025). The dual carbon emission effects of digital economy: Evidence from China. *Heliyon*, 11(6), e42554. DOI: 10.1016/j.heliyon.2025.e42554.
17. Qian, Q., Xian, B., Wang, Y., & Li, X. (2025). The impact of digital economy on carbon emissions: Based on the rebound effect. *Energy*, 333, 137345. DOI: 10.1016/j.energy.2025.137345.
18. Chen, X., & Xu, X. (2025). Enterprise Digital Transformation and Carbon Emission Performance: The Moderating Role of Economic Policy Uncertainty. *SAGE Open*. DOI: 10.1177/21582440251390795.
19. Song, Y., Xie, Z., & Song, Y. (2025). The impact of digital transformation on carbon emission intensity. *International Review of Economics & Finance*, 102. DOI: 10.1016/j.iref.2025.104302.
20. Cheng, X., et al. (2025). Digital Transformation and Corporate Carbon Emissions: Evidence from China's Listed Companies. *Sustainability*, 17(9), 3944. DOI: 10.3390/su17093944.
21. Ahmed, E. M., Elfaki, K. E., Alamin, Y. M. M., et al. (2025). Digitalization and Climate Change Spillover Effects on Saudi Digital Economy Sustainable Economic Growth. *Fudan Journal of the Humanities and Social Sciences*, 18, 687–723. DOI: 10.1007/s40647-025-00443-6.
22. Khemiri, I., & Neffati, M. (2025). The Impact of Digital Economy on Green Growth in the Kingdom of Saudi Arabia. *Economics*, 13(3), 261–282. DOI: 10.2478/eoik-2025-0065.

23. Oncu, E., Ozturk, N. S., & Erdogan, A. (2025). Sustainable development in focus: CO2 emissions and capital accumulation. *Sustainability*, 17(8), 3513. <https://doi.org/10.3390/su17083513>
24. Trinugroho, I., Achsanta, A. F., Pamungkas, P., & Sajidan, S. (2025). The impact of investment on environmental quality: Evidence from Indonesian provinces. *International Journal of Trade and Global Markets*, 21(1), 1–13. <https://doi.org/10.1504/IJTGM.2025.146310>
25. Suleman, S., Thaker, H. M. T., & Hoh, C. C. W. (2025). Is trade relevant to the macro drivers of carbon dioxide emissions? A study of high- and low-trade openness economies. *Natural Resources Forum*, 49(4), 3654–3683. <https://doi.org/10.1111/1477-8947.12543>
26. Wang, L., Pal, S., Mahalik, M. K., & Gozgor, G. (2025). Empowering sustainable development in emerging economies: The role of renewable energy and domestic investment. *Energy Economics*, 148, 108631. <https://doi.org/10.1016/j.eneco.2025.108631>
27. Alshammry, M. A. D., & Muneer, S. (2023). The influence of economic development, capital formation, and internet use on environmental degradation in Saudi Arabia. *Future Business Journal*, 9, Article 60. <https://doi.org/10.1186/s43093-023-00246-9>
28. Aldegheishem, A. (2024). The impact of air transportation, trade openness, and economic growth on CO2 emissions in Saudi Arabia. *Frontiers in Environmental Science*, 12, 1366054. <https://doi.org/10.3389/fenvs.2024.1366054>
29. Barkat, K., Alsamara, M., Al Kwifi, O. S., & Jarallah, S. (2025). Does trade openness mitigate environmental degradation in Organisation for Economic Co-operation and Development (OECD) countries? Implications for achieving sustainable development. *Natural Resources Forum*, 49(1), 677–698. <https://doi.org/10.1111/1477-8947.12412>
30. Pham, D. T. T., & Nguyen, H. T. (2024). Effects of trade openness on environmental quality: Evidence from developing countries. *Journal of Applied Economics*, 27(1), Article 2339610. <https://doi.org/10.1080/15140326.2024.2339610>
31. Mebrek, N., Louail, B., & Riache, S. (2024). Do trade openness and foreign direct investment affect CO2 emissions in the MENA region? New evidence from a panel ARDL regression. *Economics and Environment*, 4(91), 1–12. <https://doi.org/10.34659/eis.2024.91.4.972>
32. Zhou, R., Guan, S., & He, B. (2025). The impact of trade openness on carbon emissions: Empirical evidence from emerging countries. *Energies*, 18(3), 697. <https://doi.org/10.3390/en18030697>
33. Bakri, M. A., Chia, Y.-E., & Chia, R. C.-J. (2025). Trade openness and carbon emissions using threshold approach: Evidence from selected Asian countries. *Carbon Research*. <https://doi.org/10.1007/s44246-025-00211-x>
34. Derindag, O. F., & Aldawsari, S. H. (2025). Trade openness and the energy–carbon nexus: Policy implications for emerging and advanced economies. *Sustainability*, 17(23), 10762. <https://doi.org/10.3390/su172310762>
35. Sakilu, O. B., & Chen, H. (2025). Exploring the influence of trade openness, energy consumption, natural resource rents, and human capital in achieving carbon neutrality. *Regional Sustainability*, 6(4), 100247. <https://doi.org/10.1016/j.regsus.2025.100247>
36. Amer, E. A. A. A., Zhang, X., Meyad, E. M. A., Alareqi, M. M., Bather, S. M. H., & Abdelwahed, A. (2025). Urbanization, growth, and carbon footprints: A GCC perspective on sustainable development. *Sustainable Futures*, 9, 100631. DOI: 10.1016/j.sftr.2025.100631.
37. Adela, H. A., Aldhaheeri, W. B., & Ali, A. H. (2025). Dynamic Impacts of Economic Growth, Energy Use, Urbanization, and Trade Openness on Carbon Emissions in the United Arab Emirates. *Sustainability*, 17(13), 5823. DOI: 10.3390/su17135823.
38. Tunio, F. H., Nabi, A. A., Memon, R. U. R., Fraz, T. R., & Haluza, D. (2025). Sustainability in High-Income Countries: Urbanization, Renewables, and Ecological Footprints. *Energies*, 18(7), 1599. DOI: 10.3390/en18071599.
39. Mahmood, H., & Furqan, M. (2025). Renewable energy transition, urbanization, and environment nexus in the Middle East and North Africa: Cross-sectional dependence analyses. *Environmental Economics*, 16(1), 89–101. DOI: 10.21511/ee.16(1).2025.07.
40. Ma, B., & Ogata, S. (2024). Impact of Urbanization on Carbon Dioxide Emissions—Evidence from 136 Countries and Regions. *Sustainability*, 16(18), 7878. DOI: 10.3390/su16187878.
41. Qiao, W., Xie, Y., Liu, J., & Huang, X. (2025). The Impacts of Urbanization on Carbon Emission Performance: New Evidence from the Yangtze River Delta Urban Agglomeration, China. *Land*, 14(1), 12. DOI: 10.3390/land14010012.

42. Bashayreh, A., Al-Hindawi, H., & Tahtamouni, A. (2024). Modeling the urbanization rate associated with renewable in electricity production and CO2 emissions: a threshold regression approach. *Discover Sustainability*, 5, 427. DOI: 10.1007/s43621-024-00643-2.
43. Zhang, X., Meng, Q., Xu, J., & Li, K. (2025). Urbanization impacts on anthropogenic carbon dioxide emissions and the roles of urban morphologies: Insights from urban socioeconomic clusters and local climate zones in Shanghai, China. *Sustainable Cities and Society*, 118, 106494. DOI: 10.1016/j.scs.2025.106494.
44. Elimam, H., & Alattas, H. (2025). Foreign direct investment: A strategic approach towards sustainable economic growth in Saudi Arabia. *Cogent Economics & Finance*, 13(1), 2492203. <https://doi.org/10.1080/23322039.2025.2492203>.
45. Haseeb, M., Shuaib, M., Hossain, M. E., Doğan, M., & Makhmudov, S. (2026). The impact of eco-innovations, FDI, and financial development on environmental sustainability. *Discover Sustainability*, 7, 300. <https://doi.org/10.1007/s43621-025-02476-z>.
46. Pham, P. M. H., Nguyen, T. D., Nguyen, M., & Tran, N. T. (2025). FDI inflows and carbon emissions: New global evidence. *Discover Sustainability*, 6, 432. <https://doi.org/10.1007/s43621-025-01292-9>.
47. Kutlu Furtuna, O., & Atis, S. (2024). Does foreign direct investment affect environmental degradation: Evidence from largest carbon intense countries. *PLOS ONE*, 19(11), e0314232. <https://doi.org/10.1371/journal.pone.0314232>.
48. Nguyen, Q. K., Tran, D. L., Tran, X. H., Pham, N. T. N., & Nguyen, N. P. L. (2025). The complex relationship between carbon dioxide emissions, foreign direct investment, and economic growth in Asian countries. *Discover Sustainability*, 6, 831. <https://doi.org/10.1007/s43621-025-01730-8>.
49. Tripathy, P., Brahma, M., Pallayil, B., & Mishra, B. R. (2025). Mediating Effects of Foreign Direct Investment Inflows on Carbon Dioxide Emissions. *Economies*, 13(1), 18. <https://doi.org/10.3390/economies13010018>.
50. Yu, J., Majeed, A., & Liu, Y. (2025). Rethinking Foreign Direct Investment's Role in Sustainable Development: Insights from the E-7 Economies Using Advanced Panel Data Methodologies. *Sustainability*, 17(8), 3757. <https://doi.org/10.3390/su17083757>.
51. Pan, Y., Atsi, E. R., Tang, D., He, D., & Donkor, M. (2025). The Synergistic Effect of Foreign Direct Investment and Renewable Energy Consumption on Environmental Pollution Mitigation: Evidence from Developing Countries. *Sustainability*, 17(10), 4732. <https://doi.org/10.3390/su17104732>.
52. Bennaceur, M. Y., Abid, M., Elshaabany, M., Taha, T. K., Reda, Z., & Hamza, R. A. E. M. (2024). How does ICT diffusion and renewable energy consumption affect CO2 emissions? *International Journal of Energy Economics and Policy*, 15(1), 131–142. <https://doi.org/10.32479/ijee.17617>.
53. Sadaoui, N., Zabat, L., Abid, M., & Hussien, B. S. A. (2025). The moderating role of information and communication technology diffusion in informal economy-pollution nexus in Kingdom Saudi Arabia. *International Journal of Energy Economics and Policy*, 15(3), 176–185. <https://doi.org/10.32479/ijee.18501>.
54. Abid, M., Abdelli, H., Gheraia, Z., Ghandri, M., & Elshaabany, M. (2026). How does ICT diffusion affect environmental sustainability in KSA? The moderating role of financial sector. *Green Technologies and Sustainability*, 4(2), 100354. <https://doi.org/10.1016/j.grets.2026.100354>.
55. Abid, I., & Gafsi, N. (2025). Economic complexity, environmental sustainability, and technological integration in Saudi Arabia: Analyzing long-term trends. *International Journal of Energy Economics and Policy*, 15(3), 669–683. <https://doi.org/10.32479/ijee.18806>.
56. Alsuhaybany, Y. (2025). Digital innovation and circular economy: A nexus for sustainable oil and gas sector transformation in Saudi Arabia. *Sustainability*, 17(3), 1325. <https://doi.org/10.3390/su17031325>.
57. Taha, O. S., Alshibani, A., AlTuraik, A. S., Mahmoud, M. A., Mohammed, A., & Hassanain, M. A. (2025). Digital technologies and sustainability barriers in heavy construction: A structural equation modeling study on triple-bottom-line outcomes. *Results in Engineering*, 28, 107808. <https://doi.org/10.1016/j.rineng.2025.107808>.
58. Khan, M. I., Yasmeen, T., Hadi, N. U., Asif, M., Farooq, M., Kurniawan, T. A., Khan, M., & Al-Ghamdi, S. G. (2026). Digital sustainability as an emerging paradigm: Insights from the Saudi Arabian experience and global implications. *Journal of Open Innovation: Technology, Market, and Complexity*, 12(1), 100731. <https://doi.org/10.1016/j.joitmc.2026.100731>