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Economic Complexity, Environmental Sustainability, and Technological Integration in Saudi Arabia: Analyzing Long-Term Trends

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ABSTRACT

The purpose of this research paper is to examine the long-term dynamics between economic growth, technological integration, and environmental sustainability in Saudi Arabia from 1995 to 2023. It aims to identify the impact of key economic, technological, and environmental indicators, including GDP, ICT sector performance, foreign direct investment (FDI), trade, and ecological footprint, on the country's development trajectory. The research employs a quantitative approach, using VAR-VECM models to analyze time-series data. The study applies Granger causality tests and impulse response functions (IRFs) to investigate the causal relationships between variables, focusing on the effects of economic complexity (ECI), ICT, trade, FDI, and environmental sustainability. The findings reveal that economic growth, represented by GDP per capita, significantly impacts the ecological footprint over time, while trade plays a complex role in both environmental sustainability and economic diversification. Technological integration, especially through ICT exports, is closely linked to economic complexity, though foreign direct investment (FDI) appears to negatively influence the development of high-value sectors. The study also shows that while technological growth accelerates economic performance, it is accompanied by increased environmental impact, emphasizing the need for sustainable policies. The Granger causality tests indicate that the ecological footprint influences other variables, but its direct connection to GDP per capita is weak. This research contributes to the understanding of the interconnectedness between economic growth, technological development, and environmental sustainability in Saudi Arabia, providing insights for policymakers focused on achieving balanced, long-term growth. The study's originality lies in its integration of various economic, technological, and environmental dimensions to analyze Saudi Arabia's sustainable development trajectory, particularly through the lens of ICT and FDI.

Keywords: Technological Integration, Environmental Sustainability, Ecological Footprint, Economic Complexity Index, ICT Exports, Foreign Direct Investment, Sustainable Development
JEL Classification: Q56, O13, F63

1. INTRODUCTION

The global economy is increasingly driven by the dynamic interplay between economic growth, technological advancements, and environmental sustainability. In the context of the Gulf Cooperation Council (GCC) region, Saudi Arabia, as the largest economy, presents a unique case study of how these factors interact. Over the past few decades, the Kingdom has undergone significant transformations, both economically and environmentally, driven by its rich oil resources and a strong desire to diversify its economy away from oil dependency. This diversification, exemplified through initiatives such as Vision 2030, emphasizes technological innovation, industrial diversification, and sustainable development (Saudi Vision 2030, 2016). However, as the country strives to modernize its economy, the relationship between economic performance, technological integration, and environmental impacts remains underexplored.

Saudi Arabia's Vision 2030 aims to reduce the nation's reliance on oil, focusing on sectors such as tourism, entertainment, and information technology, while fostering a knowledge-based economy (Al-Fadhli, 2021). These efforts are mirrored by a steady increase in technological exports and imports, particularly in the ICT sector, where Saudi Arabia's growing participation in the digital economy is evident (Al-Ohali, 2020). At the same time, environmental sustainability remains a critical challenge, with the Kingdom's ecological footprint rising alongside its economic growth (Khamis, 2019). As Saudi Arabia transitions into a more diversified and technologically advanced economy, understanding the complex interactions between economic growth, technological progress, and environmental sustainability is crucial for developing effective policies and strategies.

The purpose of this research paper is to examine the complex dynamics between Saudi Arabia's economic growth, its integration into the global digital economy, and its environmental sustainability from 1995 to 2023. This study explores how key variables such as GDP per capita, economic complexity, ICT exports and imports, foreign direct investment (FDI), trade openness, and the per capita ecological footprint (ECOFP) interact to shape the country's development trajectory. The central question of this study is how these variables influence each other, particularly in terms of environmental sustainability and technological progress.

The research approach is rooted in advanced econometric analysis, including vector autoregressive (VAR) models, Granger causality tests, and impulse response functions, to explore causal relationships between these variables. The study focuses on the long-term effects of economic complexity and ICT trade on environmental outcomes, as well as how these variables interrelate within the broader context of Saudi Arabia's economic development goals.

By investigating these relationships, this paper contributes to a deeper understanding of the challenges and opportunities facing Saudi Arabia in balancing economic growth, technological innovation, and environmental sustainability. The findings will provide valuable insights for policymakers seeking to navigate the complexities of sustainable development in an oil-dependent economy transitioning towards a more diversified and knowledge-based economy.

The paper is structured as follows. Section 2 reviews relevant literature. Section 3 outlines the methodology, detailing the model and statistical techniques used. Section 4 introduces the dataset, including its source and preparation. Section 5 presents the empirical results and explores the implications of the results. The final section concludes the paper.

2. LITERATURE REVIEW

The interplay between economic complexity, environmental sustainability, and technological integration in Saudi Arabia has garnered significant scholarly attention, particularly considering the country's ambitious Vision 2030. This literature review critically examines a series of articles that collectively illuminate the challenges and strategies associated with this multifaceted transition.

The foundational work by Amadi et al. (2014) emphasizes the urgent need for corporate organizations to prioritize eco-efficiency, highlighting the ethical dimensions of sustainability amidst the complexities of economic growth and ecological footprints. Their analysis underscores the contested nature of sustainable development in contemporary discussions, framing it as a critical component of economic discourse that requires a reevaluation of corporate greening strategies.

Building on this foundation, Makasi and Govender (2015) introduce a conceptual model that situates globalization as a double-edged sword for sustainable development. They argue that while globalization presents opportunities for economic advancement, it also imposes significant pressures on least developed countries, complicating the balance between environmental integrity and economic welfare. This duality prompts a deeper inquiry into the ethical relationships between present and future generations, emphasizing the need for comprehensive frameworks to navigate the complexities of sustainability.

Roy (2016) critiques prevailing paradigms of economic growth and development, challenging the adequacy of conventional economic instruments in addressing environmental challenges. His exploration of the political economy reveals the intricate ties between globalization, economic models, and environmental degradation, suggesting that technological solutions often overlook fundamental ecological dynamics. This critique resonates with the call for a more nuanced understanding of the interdependencies between economic systems and environmental sustainability.

In a more recent analysis, Asiimwe and De Kock (2019) investigate the integration of industry 4.0 within sustainability transitions. Their findings highlight the gaps in literature regarding the application of sustainability concepts outside Europe, suggesting that a broader geographical focus could enhance the understanding of socio-technical transformations. This work advocates for further research to address the diverse contexts in which sustainability is enacted, particularly in emerging economies.

Sánchez-Flores et al. (2020) contribute to the discourse by examining sustainable supply chain management (SSCM) as a critical area of research. They identify the pressing need for organizations to adopt sustainable practices in their supply chains, particularly in light of rapid market changes and increasing competition. Their review underscores the importance of integrating environmental and social principles throughout the supply chain, suggesting that empirical studies in emerging economies are essential for advancing this field.

The paper by Alajmi, (2022) provides a comprehensive analysis of the interplay between economic growth, energy consumption, and environmental sustainability within the context of Saudi Arabia's reliance on fossil fuels. The author effectively highlights the urgent need for technological integration and energy efficiency to mitigate the adverse effects of carbon emissions, which have escalated significantly alongside the country's economic development.

Alajmi's examination of the structural time series model (STSM) to quantify the environmental impact of electricity generation is particularly noteworthy. This methodological approach allows for a nuanced understanding of how energy-efficient technological innovations can potentially alter the trajectory of carbon emissions in Saudi Arabia. The article's emphasis on the logarithmic mean Divisia index (LMDI) decomposition method to analyze the factors influencing carbon dioxide emissions adds depth to the discussion, offering insights into the multifaceted nature of energy consumption and its environmental repercussions. These concerns are further echoed by Abid et al. (2024b), who examine the impacts of energy intensity and CO_2 emissions on economic growth in the GCC region, reinforcing the urgency of decoupling energy use from economic expansion (Gafsi & Bakari, 2025).

The paper by Chaaben et al. (2024) presents a comprehensive examination of the intersection between economic complexity, environmental sustainability, and technological integration within the context of Saudi Arabia. The authors highlight the detrimental impacts of environmental degradation and the COVID-19 pandemic on economic resilience and social well-being, emphasizing the urgent need for innovative recovery strategies that align economic growth with sustainable practices.

A central theme of the article is the notion of a "green" stimulus as a viable pathway for recovery, which advocates for a transition towards a cleaner and more sustainable economy. This approach is particularly relevant in the context of Saudi Arabia's Vision 2030, which aims to diversify the economy and promote sustainable development in alignment with the United Nations' Sustainable Development Goals (SDGs). The authors argue that integrating climate strategies with development initiatives is crucial for fostering green, resilient, and inclusive growth.

The paper introduces a novel economic index derived from the EEPSE Green Economy Index, which is anchored in the Quintuple Helix Innovation Model. This model underscores the importance of collaboration among various stakeholders, including education, industry, government, society, and the environment. By employing this index, the authors provide a robust analytical framework for assessing the performance of Saudi Arabia's green economic initiatives and their effectiveness in achieving sustainable development goals from 2015 to 2020.

One of the paper's significant contributions is its critique of the prevailing focus in contemporary research on the renewable energy consumption-environment nexus, which often overlooks the broader implications of a green economy in bridging the gap between economic activity and sustainable development. The authors contend that this oversight has led to a lack of comprehensive studies examining the synergy between green economic practices and sustainable development in Saudi Arabia. Supporting this, Abid (2025a) provides empirical evidence on how economic and environmental variables jointly shape green growth in Saudi Arabia, emphasizing policy-level implications for transitioning towards a greener economy.

However, while the paper effectively outlines the theoretical framework and policy implications, it could benefit from a more in-depth analysis of specific case studies or empirical data to substantiate the claims made regarding the performance of green initiatives. Furthermore, a critical evaluation of the challenges faced in implementing these strategies, such as potential resistance from traditional economic sectors or the need for capacity building among stakeholders, would provide a more nuanced understanding of the complexities involved in transitioning to a green economy.

Adedoyin et al. (2022) delve into the relationship between economic complexity and environmental impact, revealing a complex interplay where higher economic complexity can lead to increased carbon emissions. Their study brings to light the challenges of transitioning to higher-productivity sectors while managing ecological consequences, prompting a reevaluation of how economic complexity is understood in relation to sustainability.

Aristi Capetillo et al. (2023) explore the role of emerging technologies in supporting the transition to a circular economy. Their systematic literature review highlights the significance of digital technologies in enhancing sustainability within the plastic materials value chain, advocating for further research to understand the synergies between technological innovation and sustainable practices.

Ellili (2024) conducts a bibliometric analysis of sustainability literature, identifying key themes and gaps in research. This study emphasizes the need for a broader focus on social and environmental sustainability, particularly within family businesses and small to medium enterprises (SMEs). The findings suggest that future research should expand beyond financial performance to explore the broader implications of sustainable practices on economic growth.

Caldarola et al. (2024) provide a comprehensive review of the empirical literature linking economic complexity to sustainability transitions. They harmonize various methods and data sources, emphasizing the potential of economic complexity approaches to inform sustainable practices. Their analysis reveals mixed evidence regarding the relationship between export complexity and environmental outcomes, highlighting the need for more granular research to capture the dynamics of economic and environmental interactions.

Hassan et al. (2023) further investigate the connections between green growth, eco-innovation, and sustainability. Their study posits that green growth strategies can yield significant social and economic benefits while addressing ecological challenges. The authors advocate for a comprehensive understanding of how technological advancements can facilitate sustainable development, particularly in underdeveloped regions.

The article by Sarabdeen and Mohamed Ishak, (2024) provides a comprehensive analysis of the intersection between intellectual property law, energy efficiency, and economic diversification in the context of Saudi Arabia's Vision 2030. The authors emphasize the critical need for strong legal frameworks to support energy-efficient innovations as the country transitions towards a lower-carbon economy.

The paper also highlights the importance of awareness and understanding of green laws among stakeholders to foster a conducive environment for innovation. By advocating for improved laws and regulations, the authors suggest that Saudi Arabia can attract foreign investment and encourage local innovations in energy efficiency. This is particularly relevant given the global shift towards sustainable practices and the increasing demand for energy-efficient technologies. Further empirical support is found in Chaabouni & Abid (2025), who identify the primary drivers of energy consumption in GCC countries and call attention to the policy mix necessary for steering the region towards a more sustainable path.

Furthermore, the authors detail the specific measures taken by the Saudi government to promote energy efficiency, including the introduction of an energy-efficient program in 2012 that encompasses a range of actions aimed at addressing energy consumption issues. The initiative's focus on upgrading outdated power plants and implementing conservation measures reflects a proactive approach to managing energy demand and reducing environmental impact.

However, a critical evaluation of the paper reveals some areas where further exploration could enhance the discussion. For instance, while the authors provide a solid overview of the policies and programs in place, there is limited examination of the challenges and barriers to the successful implementation of these initiatives. Understanding the socio-economic and political factors that may hinder progress towards a low-carbon economy would provide a more nuanced perspective on the effectiveness of the proposed strategies.

Finally, Wei et al. (2024) examine the interplay between international digital trade, green technology innovation, and environmental sustainability in emerging economies. Their research highlights the potential of green technology to enhance resource efficiency and sustainability, addressing a critical gap in understanding how globalization can align with ecological goals. This exploration of the nexus between digital trade and sustainability offers valuable insights into the future of sustainable development in a rapidly changing global landscape.

Together, these papers contribute to a rich and evolving discourse on the interplay between economic complexity, environmental sustainability, and technological integration, highlighting the need for continued research and innovative solutions to address the pressing challenges of our time.

3. METHODOLOGY

This research employs a suite of econometric methods to investigate the dynamic relationships among key variables. The analysis includes estimating a Vector Autoregression (VAR) model to capture temporal interdependencies, applying Granger causality tests to determine directional influences, conducting cointegration testing to identify long-term equilibrium relationships, and utilizing a Vector Error Correction Model (VECM) to examine both short-term dynamics and long-run adjustments. Additionally, Impulse Response Functions (IRFs) are used to assess the effects of shocks across variables over time, and variance decomposition is applied to quantify the contribution of each variable to forecast error variance.

3.1. Vector Autoregression (VAR) Estimation

The VAR model is employed to explore dynamic interrelations between multiple time series variables. This model generalizes the autoregressive model to the multivariate context. A general VAR(p) model is expressed as:

$$Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + \ldots + A_p Y_{t-p} + \varepsilon_t \quad (1)$$

Where:
Yt: An n×1 vector of endogenous variables.
Ai: An n×n matrix of coefficients at lag i.
ε_t: A vector of white noise error terms.

p: The optimal lag length, selected using criteria such as Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC) (Lütkepohl, 2005).

The VAR framework captures how past values of the variables affect their current values, allowing for dynamic interdependencies to be modeled.

3.2. Granger Causality Tests

Granger causality tests assess whether past values of one variable enhance the predictability of another. The null hypothesis assumes no causality. The Wald test statistic in a bivariate VAR system is represented as:

$$H_0: \gamma_1 = \gamma_2 = \ldots = \gamma_P = 0 \quad (2)$$

Here $\gamma_1, \gamma_2., \gamma_p$ are coefficients of the lagged terms of the independent variable. Rejecting the null indicates that the independent variable Granger-causes the dependent variable (Granger, 1969).

3.3. Cointegration Analysis

To assess long-term equilibrium relationships among non-stationary variables, Johansen's Cointegration Test is employed. The trace statistic is given by:

$$\text{Trace Statistic} = -T\sum_{i=r+1}^{n} \ln(1-\hat{\lambda}_i) \quad (3)$$

Where:
T: Sample size.
$\hat{\lambda}_i$: Eigenvalue from the cointegration matrix.
r: Number of cointegrating vectors under the null hypothesis.

If the trace statistic exceeds the critical value, it implies a stable long-run relationship among the variables (Johansen, 1991).

3.4. Vector Error Correction Model (VECM)

For cointegrated variables, a VECM is utilized to capture both short-term fluctuations and long-term equilibrium adjustments. The model is specified as:

$$\Delta Y_t = \beta Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t \quad (4)$$

Where:

ΔY_t: First difference of the endogenous variables.

βY_{t-1}: Error correction term (which adjusts for the long-run equilibrium relationship between the variables).

Γ_i: Short-term adjustment coefficients.

ε_t: Error term.

The error correction term measures the rate at which the system returns to equilibrium after a disturbance (Engle and Granger, 1987).

3.5. Impulse Response Functions (IRFs)

IRFs analyze how a 1-time shock to one variable propagates to others over time. The response at horizon hhh is given by:

$$IRF_h = B_h A^{-1} \quad (5)$$

Where:

B_h: Coefficients matrix at horizon h.

A^{-1}: Inverse of the VAR coefficient matrix.

This approach helps trace the dynamic interactions among variables following a shock (Pesaran and Shin, 1998).

3.6. Variance Decomposition

Variance decomposition quantifies the proportion of forecast error variance of each variable that can be attributed to shocks in itself or other variables. The decomposition at horizon hhh is expressed as:

$$VD_{i,h} = \frac{Var(\varepsilon_i^h)}{Var(\varepsilon_t^h)} \quad (6)$$

Where:

$Var(\varepsilon_i^h)$: Forecast error variance of variable i at horizon h.

$Var(\varepsilon_t^h)$: Total forecast error variance at horizon h.

This method reveals the relative importance of each variable in explaining fluctuations within the system (Sims, 1980).

By employing these econometric techniques, this study captures both short-term dynamics and long-term equilibrium relationships among variables, providing a comprehensive understanding of the temporal and structural interactions within the system.

4. DATA

For the analysis of Saudi Arabia from 1995 to 2023, we use the following variables to capture key aspects of economic, environmental, and technological dynamics.

- The Per capita ecological footprint (ECOFP), measured in global hectares, represents the environmental demand placed by each individual on the Earth's ecosystems and serves as a sustainability indicator (source: Global Footprint Network).
- The economic complexity index (ECI) reflects the diversity and sophistication of a country's export structure, highlighting economic diversification and knowledge intensity (source: The Observatory of Economic Complexity).
- To evaluate technological integration, we include ICT Goods Exports (ICTE) and ICT Goods Imports (ICTI) as percentages of total goods exports and imports, respectively, indicating the level of engagement in the global digital economy (source: WDI).
- For economic growth and standard of living, we consider GDP per Capita (GDP), adjusted to constant 2015 US dollars, which provides a measure of average economic output per person (source: WDI).
- Additionally, as control variables, Foreign Direct Investment (FDI), measured as net inflows relative to GDP, assesses the country's ability to attract external investment, while Trade Openness (TRA), expressed as the percentage of GDP derived from the sum of exports and imports, captures the degree of global economic integration (source: WDI).

To normalize data and reduce variability, logarithmic transformations are applied to ECOFP, GDP, and TRA where necessary. Together, these variables provide a comprehensive framework for assessing Saudi Arabia's progress in sustainability, economic diversification, and global competitiveness.

The correlation matrix provides insights into the relationships between key economic, environmental, and technological variables for Saudi Arabia (Table 1).

The ecological footprint (ECOFP) shows a strong positive correlation with economic complexity index (ECI), indicating that higher economic diversification and sophistication are associated with increased ecological demand. Similarly, ECOFP has strong positive correlations with ICT Imports (ICTI) and GDP per capita (GDPPCC), suggesting that economic growth and reliance on imported technology contribute to greater environmental impact.

The economic complexity index (ECI) also correlates strongly with GDP per capita, highlighting the role of economic diversification in driving income levels. Additionally, ECI has a moderate positive correlation with ICTI, reflecting the link between technological imports and economic complexity. ICT Exports (ICTE) shows a moderate positive correlation with ECOFP, suggesting that technological exports may slightly increase environmental impact, while its correlation with GDP per capita is weaker.

Foreign direct investment (FDI) displays weak correlations overall, with its strongest relationship being with ICTE, implying that foreign investment modestly supports technological exports. Conversely, Trade openness (TRA) shows a negative correlation with ECI, indicating that greater trade openness might coincide with lower economic complexity. TRA also has a weak negative relationship with ECOFP, suggesting a slight reduction in ecological footprint with increased trade activity.

Table 1: Correlation matrix

Variable	ECOFP	ECI	ICTE	ICTI	GDPPCC	FDI	TRA
ECOFP	1.0000						
ECI	0.8268	1.0000					
ICTE	0.5244	0.5752	1.0000				
ICTI	0.7818	0.6842	0.4830	1.0000			
GDPPCC	0.6596	0.7719	0.3465	0.5739	1.0000		
FDI	0.4448	0.3340	0.4999	0.3664	0.3275	1.0000	
TRA	−0.1502	−0.5567	−0.3340	0.0269	−0.2992	0.0047	1.0000

Table 2: Descriptive statistics

Variable	Observations	Mean	Standard deviation	Min	Max
ECOFP	28	1.5499	0.2789	0.8578	1.9247
ECI	28	0.5274	0.2584	0.1636	0.9108
ICTE	22	0.1200	0.0949	0.0000	0.4000
ICTI	22	6.8195	1.1105	4.1500	8.1800
GDPPCC	29	10.0050	0.0536	9.8873	10.0984
FDI	29	0.7390	1.1578	−1.3078	3.2965
TRA	29	4.2474	0.1722	3.9063	4.5654

Overall, the matrix highlights significant trade-offs between economic growth, environmental sustainability, and technological integration, underscoring the complexity of Saudi Arabia's development trajectory.

The summary statistics in Table 2 provide an overview of the key variables for Saudi Arabia.

The per capita ecological footprint (ECOFP) has a mean of 1.5499 (log-transformed), with notable variation (standard deviation of 0.2789) and a range from 0.8578 to 1.9247, reflecting fluctuations in environmental demand. The economic complexity index (ECI) averages 0.5274, indicating moderate economic diversification, with values ranging from 0.1636 to 0.9108. ICT goods exports (ICTE) represent a small fraction of total exports, with a mean of 0.12 and a maximum of 0.40, suggesting limited engagement in ICT export activities. Conversely, ICT goods imports (ICTI) show a high average of 6.8195, reflecting significant reliance on imported ICT products, with values ranging from 4.15 to 8.18. GDP per capita (GDPPCC), log-transformed, exhibits a mean of 10.0050 with minimal variation (standard deviation of 0.0536), indicating relatively stable economic growth over the period. Foreign Direct Investment (FDI) displays the highest variability, with an average of 0.7390 and a range from −1.3078 (net outflows) to 3.2965 (net inflows), highlighting fluctuations in foreign investment inflows. Finally, trade openness (TRA), log-transformed, has a consistent mean of 4.2474, with a narrow range from 3.9063 to 4.5654, reflecting relatively stable trade activity as a percentage of GDP. These statistics provide a clear picture of Saudi Arabia's economic and environmental trends over nearly three decades.

5. RESULTS AND DISCUSSION

The methodology for the vector autoregression (VAR) analysis begins with a stationarity check, where unit root tests such as the Augmented Dickey-Fuller are conducted to ensure the time series data are stationary. If the data are non-stationary, differencing is applied to achieve stationarity.

Table 3: Dickey-fuller test results

Variable	Z Statistic	P-value	Conclusion
ECOFP	−1.4050	0.5798	Unit root present
ECI	−0.6160	0.8672	Unit root present
ICTE	−1.2930	0.6322	Unit root present
ICTI	−2.7020	0.0737	Unit root present
GDPPCC	−2.0310	0.2730	Unit root present
FDI	−4.2690***	0.0005	No unit root
TRA	−1.2960	0.6310	Unit root present
ΔECOFP	−5.8810***	0.0000	No unit root
ΔECI	−3.9970***	0.0014	No unit root
ΔICTE	−4.3340***	0.0004	No unit root
ΔICTI	−6.5280***	0.0000	No unit root
ΔGDPPCC	−5.3220***	0.0000	No unit root
ΔFDI	−6.2430***	0.0000	No unit root
ΔTRA	−4.3650***	0.0003	No unit root

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

The Dickey-Fuller test checks for the presence of a unit root, indicating whether a time series is stationary or non-stationary. The null hypothesis is that the series has a unit root (Table 3).

Most original variables are non-stationary except FDI. After differencing, all variables become stationary, indicating that the time series data should be analyzed using their first differences to ensure stationarity.

The optimal lag length for the VAR model is determined using criteria such as the Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (SBC), or Hannan-Quinn Criterion (HQC). Once the lag length is identified, the VAR model is estimated, capturing the interdependence among variables over time. Table 4 provides the results of various lag selection criteria for the VAR model.

Based on the results, Lag 2 is the optimal lag for the model since it minimizes the selection-order criteria (FPE, AIC, HQIC, and SBIC) and provides a statistically significant improvement over previous lag.

Table 5 provides vector autoregression (VAR) model estimates. Each equation shows strong significance and explains a substantial proportion of variance in the dependent variable. The VAR model does a good job of explaining the relationships between the

Table 4: Selection-order criteria

Lag	LL	LR	df	P-value	FPE	AIC	HQIC	SBIC
0	93.9166	-	-	-	2.5×10^{-13}	−9.1491	−9.0902	−8.8012
1	129.28	70.7260	49	0.0230	1.6×10^{-12}	−7.7136	−7.2425	−4.9300
2	1222.060	2185.6*	49	0.0000	1.0×10^{-58}*	−117.585*	−116.701*	−112.365*

Table 5: VAR estimation

Model characteristics		ΔECOFP equation	ΔECI equation	ΔICTE equation	ΔICTI equation	ΔGDPCC equation	FDI equation	ΔTRA equation
R-squared		0.8912	0.7728	0.6602	0.8002	0.8103	0.7382	0.9108
Chi-squared		155.6474	64.6194	36.9139	76.0934	81.1648	53.5853	194.0475
P-value		0.0000	0.0000	0.0008	0.0000	0.0000	0.0000	0.0000
Variable	**Lag**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**
ΔECOFP	L1	−0.1615**	0.0488	0.1991	−1.9094	−0.0976	10.7763***	−0.1712
		(0.0843)	(0.1902)	(0.2427)	(1.3442)	(0.0817)	(2.2011)	(0.1255)
	L2	0.2586**	0.4028	−0.7836***	−5.8290***	0.0902	−6.3051**	−0.0929
		(0.1125)	(0.2537)	(0.3239)	(1.7934)	(0.1090)	(2.9366)	(0.1674)
ΔECI	L1	0.1688***	−0.1161	−0.3164**	−2.7839***	0.0925*	−0.7321	−0.1548*
		(0.0557)	(0.1256)	(0.1603)	(0.8876)	(0.0540)	(1.4534)	(0.0828)
	L2	0.2375***	−0.3300***	0.4334***	−1.1059	−0.0982*	−3.2092**	−0.1554*
		(0.0593)	(0.1338)	(0.1707)	(0.9455)	(0.0575)	(1.5482)	(0.0883)
ΔICTE	L1	0.0570	−0.1818	0.1394	1.5497	0.3284***	7.7054***	1.0546***
		(0.1060)	(0.2390)	(0.3051)	(1.6896)	(0.1027)	(2.7667)	(0.1577)
	L2	0.9328***	1.2437***	−0.0880	4.7648***	0.1210	−3.0344	0.3634**
		(0.1092)	(0.2464)	(0.3146)	(1.7421)	(0.1059)	(2.8526)	(0.1626)
ΔICTI	L1	0.0505***	0.0509**	−0.0041	−0.5496***	0.0154	0.2852	0.0195
		(0.0100)	(0.0225)	(0.0287)	(0.1589)	(0.0097)	(0.2602)	(0.0148)
	L2	0.0082	0.0717***	−0.0006	−0.2239	0.0216**	−0.0662	0.0683***
		(0.0099)	(0.0224)	(0.0286)	(0.1584)	(0.0096)	(0.2593)	(0.0148)
ΔGDPCC	L1	−0.0563	0.4344	0.7827	2.7372	0.1845	13.5381***	−0.0647
		(0.2108)	(0.4756)	(0.6071)	(3.3616)	(0.2044)	(5.5045)	(0.3138)
	L2	0.3529**	2.0454***	0.0661	0.6108	−0.3327*	−1.5142	0.2645
		(0.1838)	(0.4147)	(0.5294)	(2.9315)	(0.1782)	(4.8003)	(0.2736)
FDI	L1	−0.0070	−0.0500***	0.0013	0.3339***	−0.0152**	0.2115	0.0093
		(0.0073)	(0.0164)	(0.0210)	(0.1161)	(0.0071)	(0.1902)	(0.0108)
	L2	−0.0252***	0.0216	0.0168	−0.2523***	0.0053	0.2890*	−0.0201**
		(0.0063)	(0.0142)	(0.0181)	(0.1003)	(0.0061)	(0.1642)	(0.0094)
ΔTRA	L1	−0.3493***	−0.5847***	−0.5370**	2.8435**	0.0567	−4.7689**	0.9805***
		(0.0937)	(0.2114)	(0.2698)	(1.4941)	(0.0908)	(2.4465)	(0.1395)
	L2	0.5962***	−0.1344	0.6144**	−1.1109	−0.2442***	2.1949	−0.7526***
		(0.0975)	(0.2200)	(0.2809)	(1.5553)	(0.0946)	(2.5468)	(0.1452)
_cons	–	0.0104	0.0209	0.0032	0.4642***	0.0073	0.3676	−0.0062
		(0.0091)	(0.0205)	(0.0262)	(0.1452)	(0.0088)	(0.2377)	(0.0136)

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

variables over time. This indicates that each of these variables has a significant intertemporal relationship, and the model likely provides a good fit for forecasting and understanding their joint dynamics.

The VAR regression analysis highlights several key insights into the dynamics of Saudi Arabia's economic, environmental, and technological factors from 1995 to 2023.

- In this model, the ECOFP is mainly influenced by several key variables, notably Economic Complexity and ICT exports/imports, which have significant long-term effects. The positive relationship with ICT goods exports (L2) and imports (L1) suggests that the growth in these sectors is closely tied to higher resource consumption and environmental impact, highlighting the resource-intensive nature of ICT industries. Trade also plays a dual role: Short-term increases in trade reduce ECOFP, while long-term trade activities contribute to higher environmental impact, potentially due to increased transportation emissions. The results indicate that foreign direct investment has a long-term negative effect, possibly due to its role in promoting cleaner technologies or more efficient industries. The role of GDP per capita is mixed: While short-term growth does not have a significant impact, long-term growth is associated with increased ecological footprint, likely due to higher consumption patterns associated with wealthier economies. This analysis underlines the complex and lagged nature of the relationships between economic activity and environmental outcomes.
- The ΔECI equation reveals that ICT exports and imports, along with GDP growth, have significant effects on changes in economic complexity. Particularly, ICT exports from the past two periods play a crucial role in driving economic complexity, with a strong positive effect. Similarly, ICT imports also contribute positively, highlighting the importance of integrating advanced technologies into the economy. The

negative effect of FDI (L1) suggests that foreign investments may not always contribute to increasing economic complexity, possibly due to a focus on less complex industries. In contrast, trade (ΔTRA) appears to have a negative relationship with economic complexity, especially in the short term, potentially due to trade's reliance on less complex sectors or goods. This model emphasizes the importance of technology (ICT sector) and GDP growth in fostering economic complexity, while also suggesting that trade and FDI may need to be managed carefully to align with economic diversification and sophistication goals.

- The ΔICTE equation reveals a complex relationship between ICT exports and several key economic variables. Trade (ΔTRA) has a mixed influence, with a negative short-term effect but a significant positive impact in the medium term. Economic complexity (ΔECI) has a significant relationship with ICT exports, with a negative short-term effect but a positive medium-term effect, suggesting that a complex economy might rely more on ICT exports as it diversifies. Ecological footprint plays a significant role, with a negative effect from the second lag, suggesting that increased environmental concern could hinder ICT export growth. However, GDP and FDI appear to have a minor and insignificant effect on ICT exports, indicating that these factors might not play a central role in shaping ICT export dynamics. Overall, the model emphasizes the importance of economic complexity, trade dynamics, and environmental concerns in influencing the export of ICT goods.
- The ΔICTI equation highlights several important relationships with significant lags, suggesting that the dynamics of ICT imports are influenced by both recent and past economic developments. Trade and FDI play a prominent role, with FDI having a positive short-term and negative medium-term effect on ICT imports, indicating that foreign investment first increases ICT imports but eventually leads to a decline as local industries grow. Economic complexity and ecological footprint also have notable effects, with the latter showing a strong negative impact after two periods, possibly due to environmental regulations that reduce the demand for ICT imports. ICT exports positively influence ICT imports in the longer term, suggesting a global relationship where growth in one direction leads to reciprocal flows. The mixed results for GDP and ICT imports (at different lags) suggest that economic growth and past imports do not always align with immediate changes in ICT imports. Overall, the model emphasizes the role of trade, foreign investment, and past economic activity in determining the dynamics of ICT imports.
- The ΔGDPCC equation shows that ICT exports are a significant driver of GDP growth, with a positive and highly significant impact, particularly in the short term. Economic complexity also influences GDP growth, showing a positive effect in the short run but a potential negative effect in the long term. ICT imports have a positive influence on economic growth over time, suggesting the importance of technological integration. FDI has a negative short-term impact on GDP growth, though its long-term effect remains unclear. Trade exhibits a complex relationship with GDP growth, with short-term trade changes having little impact, while long-term trade dynamics show a negative effect. These findings indicate that the ICT sector, particularly through exports, plays a key role in economic growth, while FDI and trade need to be managed carefully due to their mixed effects over time.
- The FDI equation underscores several important determinants of foreign direct investment, with a particularly strong influence from GDP growth, ICT exports, and ecological footprint. The positive impact of GDP growth in the short term highlights the importance of economic expansion in attracting foreign investment. The significant effect of ICT exports also suggests that a growing ICT sector can draw foreign capital, indicating the importance of technological innovation and global competitiveness in foreign investment decisions. On the other hand, trade and economic complexity show more nuanced effects, with trade having a negative influence and economic complexity exhibiting a discouraging impact over time. The model also indicates that the effect of ecological footprint changes with time, starting positive and later turning negative, reflecting the complex relationship between environmental sustainability concerns and investment flows. Furthermore, FDI itself has a small, marginally significant lagged effect, suggesting that past foreign investment can mildly influence future flows. Overall, the equation suggests that foreign direct investment is influenced by both short-term economic growth and trade dynamics, as well as by longer-term technological development and environmental factors.
- The ΔTRA equation indicates that ICT exports and past trade levels are the most significant drivers of changes in trade. The positive impact of ICT exports (both in the short and long term) shows how the growth of the ICT sector can enhance trade by improving competitiveness and opening new international markets. Additionally, the momentum effect of trade, where past increases in trade lead to further growth, is also observed. On the other hand, the equation suggests that economic complexity and FDI (especially over time) tend to have a negative impact on trade. Increases in economic complexity may reduce the need for international trade by focusing on more specialized industries, while past foreign investment could reduce future trade by encouraging local production. Finally, the negative effect of the ecological footprint in the first and second lags points to environmental concerns potentially slowing trade, though this effect is weak and not statistically significant. In summary, ICT exports play a central role in promoting trade, while economic complexity and foreign direct investment have a more complex, sometimes inhibitive, effect on trade in the longer term.

Following estimation, diagnostic tests are conducted to check for the validity of the VAR model. Table 6 shows the results of a Breusch-Godfrey LM test for autocorrelation and a test to detect heteroskedasticity.

The results of the diagnostic tests indicate that there are no significant issues with the model. The Breusch-Godfrey LM test shows no evidence of autocorrelation, as the $P = 0.6423$ is >0.05 significance level, meaning we fail to reject the null hypothesis of no autocorrelation. Additionally, the heteroscedasticity test also provides no evidence of heteroscedasticity, with a $P = 0.5109$, which is also above the 0.05 threshold, leading us to fail

Table 6: Test Results for autocorrelation and heteroscedasticity

Test	Statistic	P-value	Conclusion
Breusch-Godfrey LM Test	0.2160	0.6423	No evidence of autocorrelation
Heteroscedasticity test	0.3758	0.5109	No evidence of heteroscedasticity

Table 7: Granger causality wald tests

Equation	Excluded	Chi-square	Conclusion
ΔECOFP	ECI	25.356***	Causal relationship exists
	ΔICTE	75.844***	Causal relationship exists
	ΔICTI	27.743***	Causal relationship exists
	ΔGDPPCC	3.867	No causal relationship
	FDI	18.718***	Causal relationship exists
	ΔTRA	37.376***	Causal relationship exists
	ALL	149.73***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
ΔECI	ECOFP	2.719	No causal relationship
	ΔICTE	30.002***	Causal relationship exists
	ΔICTI	11.282***	Causal relationship exists
	ΔGDPPCC	32.191***	Causal relationship exists
	FDI	10.351***	Causal relationship exists
	ΔTRA	15.681***	Causal relationship exists
	ALL	57.689***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
ΔICTE	ECOFP	6.146**	Causal relationship exists
	ΔECI	10.293***	Causal relationship exists
	ΔICTI	0.022	No causal relationship
	ΔGDPPCC	2.036	No causal relationship
	FDI	0.907	No causal relationship
	ΔTRA	5.506**	Causal relationships exist
	ALL	28.322***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
ΔICTI	ECOFP	13.857***	Causal relationship exists
	ΔECI	11.241***	Causal relationship exists
	ΔICTE	7.530**	Causal relationship exists
	ΔGDPPCC	0.938	No causal relationship
	FDI	12.561***	Causal relationship exists
	ΔTRA	3.905	No causal relationship
	ALL	57.677***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
ΔGDPPCC	ECOFP	1.906	No causal relationship
	ΔECI	5.824**	Causal relationships exist
	ΔICTE	10.325***	Causal relationship exists
	ΔICTI	5.542*	Causal relationships exist
	FDI	4.902*	Causal relationships exist
	ΔTRA	7.996**	Causal relationship exists
	ALL	55.466***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
FDI	ΔECOFP	26.477***	Causal relationship exists
	ΔECI	4.560	No causal relationship
	ΔICTE	11.148***	Causal relationship exists
	ΔICTI	1.821	No causal relationship
	ΔGDPPCC	6.381**	Causal relationship exists
	ΔTRA	3.946	No causal relationship
	ALL	53.378***	Causal relationships exist
Equation	**Excluded**	**Chi-square**	**Conclusion**
ΔTRA	ECOFP	2.381	No causal relationship
	ΔECI	6.622**	Causal relationship exists
	ΔICTE	44.995***	Causal relationship exists
	ΔICTI	21.784***	Causal relationship exists
	ΔGDPPCC	0.953	No causal relationship
	FDI	4.852*	Causal relationships exist
	ALL	185.41***	Causal relationships exist

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

to reject the null hypothesis of constant error variance. These findings suggest that the model is free from autocorrelation and heteroscedasticity, supporting the robustness and reliability of the results.

Granger causality tests are conducted to establish the direction of influence among variables (Table 7).

- The results from the Granger causality test reveal that ECOFP (per capita ecological footprint) has significant causal relationships with several key variables in the model. Specifically, there is evidence of causality between ECOFP and ECI (Economic Complexity Index), ICTE (ICT goods exports), ICTI (ICT goods imports), FDI (Foreign Direct Investment), and TRA (Trade). This suggests that fluctuations in the ecological footprint are likely to influence these economic indicators. However, no causal relationship was found between ECOFP and GDP per capita (ΔGDPPCC), as indicated by the non-significant chi-square statistic. Overall, the test results support the notion that ECOFP plays a role in driving changes in various economic and trade variables, except for GDP per capita, which is not influenced by ECOFP in this analysis.
- The Granger causality test results for ECI (Economic Complexity Index) indicate that there is no causal relationship between ECI and ECOFP (per capita ecological footprint), as the chi-square statistic of 2.719 is not statistically significant. However, ECI is found to have causal relationships with several other variables, including ICTE (ICT goods exports), ICTI (ICT goods imports), GDP per capita (ΔGDPPCC), FDI (Foreign Direct Investment), and TRA (Trade). These findings suggest that changes in ECI influence these variables significantly. Overall, the test results demonstrate that ECI has a broad impact on economic complexity, ICT-related metrics, and trade, though it does not directly cause changes in the ecological footprint (ECOFP).
- The Granger causality test results for ICTE (ICT goods exports) show a causal relationship between ICTE and ECOFP (per capita ecological footprint), as evidenced by the statistically significant chi-square value of 6.146. Additionally, ICTE exhibits a causal relationship with ECI (Economic Complexity Index), as indicated by the chi-square value of 10.293, which is statistically significant. However, no causal relationship was found between ICTE and ICTI (ICT goods imports), GDP per capita (ΔGDPPCC), FDI (Foreign Direct Investment), and TRA (Trade), as their chi-square values are not statistically significant. Overall, the findings suggest that ICTE significantly impacts ECOFP and ECI, but its influence does not extend to some of the other variables tested. The overall chi-square for the complete model is statistically significant, indicating the presence of causal relationships across the variables tested.
- The Granger causality test results for ICTI (ICT goods imports) indicate a causal relationship with several variables. There is a significant causal relationship between ICTI and ECOFP (per capita ecological footprint). Similarly, ICTI exhibits a causal relationship with ECI (Economic Complexity Index), and ICTE (ICT goods exports). However, no causal relationship

was found between ICTI and GDP per capita (ΔGDPPCC), TRA (Trade), and FDI (Foreign Direct Investment. The overall chi-square for the complete model is significant, suggesting the presence of causal relationships between the variables tested, particularly with ECOFP, ECI, and ICTE.

- The results from the Granger causality test for GDP per capita (ΔGDPPCC) reveal mixed findings. There is no causal relationship between GDP per capita and ECOFP (per capita ecological footprint). However, GDP per capita shows significant causal relationships with several other variables: ECI (Economic Complexity Index), ICTE (ICT goods exports), ICTI (ICT goods imports), FDI (Foreign Direct Investment), and TRA (Trade). Overall, the chi-square value of 55.466 suggests that causal relationships exist across the model, particularly with ECI, ICTE, ICTI, FDI, and TRA.
- The results from the Granger causality test for FDI (Foreign Direct Investment) indicate several significant causal relationships. There is a causal relationship between FDI and ECOFP (per capita ecological footprint). Similarly, FDI shows a significant causal relationship with ICTE (ICT goods exports), and with GDP per capita (ΔGDPPCC). However, there is no causal relationship between FDI and ECI (Economic Complexity Index), ICTI (ICT goods imports), and TRA (Trade), all of which are not significant. The overall chi-square statistic of 53.378 suggests that causal relationships exist, particularly with ECOFP, ICTE, and GDP per capita.
- The results from the Granger causality test for TRA (Trade) indicate several notable causal relationships. There is no causal relationship between TRA and ECOFP (per capita ecological footprint). However, TRA shows a significant causal relationship with ECI (Economic Complexity Index), and with ICTE (ICT goods exports). There is also a significant causal relationship between TRA and ICTI (ICT goods imports). Additionally, TRA shows a significant causal relationship with FDI (Foreign Direct Investment). The overall chi-square statistic of 185.41 suggests that causal relationships exist, particularly with ECI, ICTE, ICTI, and FDI.

The cointegration test results, as presented in Table 8, are intended to assess whether a long-run equilibrium relationship exists among the variables. This test checks if the variables are jointly stationary in the long term, despite their individual trends or non-stationarity. A significant test statistic above the critical value would indicate the presence of cointegration, meaning that the variables are interconnected in the long run. If the cointegration test reveals multiple cointegrating vectors, it suggests the existence of several long-term relationships.

The Johansen Cointegration Test indicates the presence of cointegration among the variables. The test concludes that there are 1 cointegrating relationship in the model.

The results of the cointegration test are presented in Table 9.

The cointegration test results show a significant long-run relationship among the variables. This indicates the rejection of the null hypothesis of no cointegration, confirming that the variables are cointegrated and exhibit a stable long-term relationship.

The estimates of cointegration equation are provided in Table 10.

The cointegration analysis reveals that GDP per capita (ΔGDPPCC) has a significant negative impact on the ecological footprint, suggesting that wealthier countries may have lower ecological footprints. On the other hand, Economic Complexity (ΔECI), ICT goods imports (ΔICTI), Foreign Direct Investment (FDI), and Trade openness (ΔTRA) do not show statistically significant effects on the ecological footprint in this model. Although ICT exports show marginal relationships, their effects are not strong enough to draw definitive conclusions. This analysis highlights the importance of economic wealth (GDP per capita) in influencing ecological sustainability while suggesting that technological variables may require further investigation to establish clearer links to ecological outcomes.

The Vector Error Correction Model (VECM) is estimated to capture both short-term dynamics and long-term equilibrium relationships (Table 11).

The results from the Vector Error-Correction Model (VECM) reveal that most of the explanatory variables, including ecological footprint, economic complexity, ICT exports, ICT imports, GDP per capita, FDI, and trade, do not have significant impacts on the changes in ecological footprint, economic complexity, and trade openness. A few marginal relationships were observed, such as the weak influence of past ecological footprint values on the change in ecological footprint and the possible impact of ICT goods exports on GDP per capita. The only notable findings are the significant negative effect of ICT imports on their own changes, the positive relationship between ecological footprint and FDI, and the strong influence of ICT exports on FDI. Additionally, past values of FDI negatively affect current FDI. Overall, the results indicate that the model does not show strong or significant relationships between most variables and the changes in the indicators being analyzed.

Table 8: Johansen cointegration test results

Rank	Parameters	Log-Likelihood (LL)	Eigenvalue	Trace statistic	Critical value (5%)
0	7	60.1852	-	131.8533	124.2400
1	20	80.5729	0.8698	91.0779*	94.1500
2	31	95.3010	0.7707	61.6217	68.5200
3	40	105.8162	0.6506	40.5914	47.2100
4	47	113.0197	0.5134	26.1843	29.6800
5	52	119.7922	0.4920	12.6392	15.4100
6	55	124.3652	0.3670	3.4933	3.7600
7	56	126.1119	0.1603	-	-

The impulse response functions (IRFs) in the graphs depict the dynamic relationships between the change in the ecological footprint (ΔECOFP) and various shocks to the explanatory variables, including economic complexity (ΔECI), ICT goods exports (ΔICTE), ICT goods imports (ΔICTI), GDP per capita (ΔGDPPCC), foreign direct investment (FDI), and trade (ΔTRA) (Figure 1).

The impulse response function (IRF) analysis reveals the dynamic effects of shocks to various explanatory variables on the ecological footprint (ΔECOFP) over a 10-step period. A shock to the ecological footprint itself (ΔECOFP → ΔECOFP) results in a positive response that stabilizes over time, indicating a persistent but diminishing effect. Economic complexity (ΔECI) shows a small initial positive impact on the ecological footprint, which quickly levels off. ICT goods exports (ΔICTE) exhibit a slightly positive initial effect, which also diminishes in subsequent steps.

Table 9: Cointegration test results

Equation	Parms	Chi-square	P-value
_ce1	6	12.4285**	0.05

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

Table 10: The cointegrating equation results

Variable	Coefficient	Standard error	z-statistic	P-value
ΔECOFP	1.0000	-	-	-
ΔECI	0.8479	0.8724	0.9700	0.3310
ΔICTE	−3.2532*	1.8572	−1.7500	0.0800
ΔICTI	0.1328	0.1830	0.7300	0.4680
ΔGDPPCC	−7.8186***	2.4782	−3.1600	0.0020
FDI	−0.0326	0.0904	−0.3600	0.7190
ΔTRA	1.0641	0.8687	1.2200	0.2210
_cons	0.0161	-	-	-

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

On the other hand, ICT goods imports (ΔICTI) display a relatively stronger immediate positive impact on the ecological footprint, stabilizing after a few periods. GDP per capita (ΔGDPPCC) has a minimal and slightly negative effect, suggesting limited influence on ecological footprint changes. Foreign direct investment (FDI) shows a small initial negative impact, which stabilizes quickly, indicating a short-lived influence. Lastly, trade (ΔTRA) exhibits an initial negative response, but this effect diminishes and stabilizes over time. Overall, while some variables exert immediate effects on the ecological footprint, their influence tends to stabilize or diminish in the longer term, highlighting the transitory nature of most shocks in this context.

Table 12 provides the response of the ecological footprint (ΔECOFP) to changes in various explanatory variables (economic complexity, ICT goods exports and imports, GDP per capita, FDI, and trade) across 10 periods.

The impulse response function (IRF) results show the response of the ecological footprint (Δecofp) to changes in various explanatory variables over a period of 10 steps. Initially, at step 0, the response is 0.0798, which represents the baseline effect of the explanatory variables on the ecological footprint. As time progresses from step 1 to step 10, the coefficients for all variables gradually change, but the effects remain relatively small, indicating weak responses over time.

In terms of the individual explanatory variables, the impact of economic complexity (ΔECI) on the ecological footprint shows a marginal increase at step 1 (0.0081), but the effect decreases in subsequent periods, with no significant long-term impact. ICT goods exports (ΔICTE) show a slight positive effect at step 1 (0.0095), but similarly, the influence diminishes as time

Table 11: Vector error-correction model estimation results

Model characteristics		DΔECOFP equation	DΔECI equation	DΔICTE equation	DΔICTI equation	DΔGDPCC equation	DFDI equation	DΔTRA equation
R-squared		0.4844	0.4182	0.6261	0.7103	0.4841	0.8047	0.5271
Chi-squared		9.3950	7.1890	16.7490	24.5240	9.3850	41.2080	11.1440
P-value		0.4016	0.6174	0.0528	0.0035	0.4025	0.0000	0.2660
Variable	**Lag**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**	**Coefficient**
_ce1	L1	−0.0116	−0.2136	−0.1200	−1.8775*	0.1172	−0.8895	−0.0522
		(0.1018)	(0.1651)	(0.1455)	(1.0835)	(0.0861)	(1.0671)	(0.1425)
ΔECOFP	LD	−0.5245**	0.0773	0.6373	−0.0371	−0.1778	10.9558***	0.0389
		(0.2791)	(0.4526)	(0.3989)	(2.9699)	(0.2359)	(2.9250)	(0.3905)
ΔECI	LD	0.1291	−0.1953	−0.3509	−0.8823	0.1184	1.5839	0.1886
		(0.1497)	(0.2428)	(0.2140)	(1.5933)	(0.1266)	(1.5692)	(0.2095)
ΔICTE	LD	−0.2930	−0.7909*	−0.7566**	−5.4827**	0.4469**	5.9900**	0.5626
		(0.2694)	(0.4369)	(0.3851)	(2.8670)	(0.2277)	(2.8237)	(0.3770)
ΔICTI	LD	0.0132	0.0259	0.0025	−0.5443**	−0.0114	0.3375	−0.0202
		(0.0215)	(0.0349)	(0.0307)	(0.2289)	(0.0182)	(0.2254)	(0.0301)
ΔGDPPCC	LD	−0.3534	−1.1127	0.0662	−7.6856	0.0688	8.7920	−0.5057
		(0.5969)	(0.9680)	(0.8533)	(6.3526)	(0.5046)	(6.2565)	(0.8353)
FDI	LD	0.0027	−0.0305	−0.0193	0.1150	−0.0090	−0.4578**	0.0130
		(0.0198)	(0.0320)	(0.0282)	(0.2102)	(0.0167)	(0.2071)	(0.0276)
ΔTRA	LD	−0.2787	−0.2568	−0.5506	1.5113	0.1616	−4.0352	0.5353
		(0.3347)	(0.5427)	(0.4784)	(3.5617)	(0.2829)	(3.5078)	(0.4683)
_cons	-	−0.0009	0.0017	0.0092	−0.0319	0.0043	0.0662	0.0003
		(0.0171)	(0.0277)	(0.0244)	(0.1817)	(0.0144)	(0.1790)	(0.0239)

***, **, and *imply the significance at 1%, 5%, and 10% level, respectively

Figure 1: The impulse response functions (IRFs)

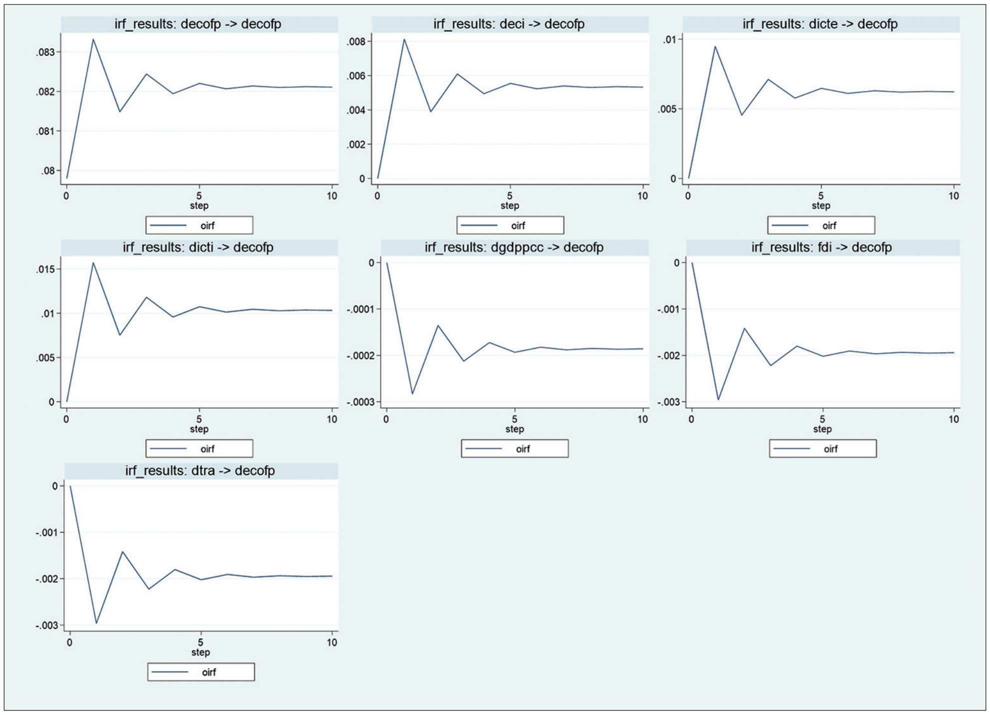

Table 12: IRF results

Step	Response to eco-footprint	Response to economic complexity	Response to ICT goods exports	Response to ICT goods imports	Response to GDP per capita	Response to FDI	Response to trade
0	0.0798	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	0.0833	0.0081	0.0095	0.0157	−0.0003	−0.0030	−0.0030
2	0.0815	0.0039	0.0045	0.0075	−0.0001	−0.0014	−0.0014
3	0.0824	0.0061	0.0071	0.0118	−0.0002	−0.0022	−0.0022
4	0.0819	0.0049	0.0058	0.0096	−0.0002	−0.0018	−0.0018
5	0.0822	0.0055	0.0065	0.0107	−0.0002	−0.0020	−0.0020
6	0.0821	0.0052	0.0061	0.0101	−0.0002	−0.0019	−0.0019
7	0.0821	0.0054	0.0063	0.0104	−0.0002	−0.0020	−0.0020
8	0.0821	0.0053	0.0062	0.0103	−0.0002	−0.0019	−0.0019
9	0.0821	0.0054	0.0063	0.0104	−0.0002	−0.0020	−0.0020
10	0.0821	0.0053	0.0062	0.0103	−0.0002	−0.0019	−0.0019

progresses. ICT goods imports (ΔICTI), foreign direct investment (FDI), and trade (ΔTRA) show relatively minor and fluctuating effects over time, with their coefficients remaining close to zero in most periods.

GDP per capita (ΔGDPPCC) has an initial negative effect on the ecological footprint at step 1 (−0.00028), but this impact is weak and continues to be marginal throughout the periods. The small and gradual changes in the response variable across these time steps suggest that while the explanatory variables do have some influence on the ecological footprint, these impacts are not strong or significant in the short term. In conclusion, the results indicate that the variables analyzed (economic complexity, ICT trade, GDP, FDI, and trade) have weak and short-lived effects on changes in the ecological footprint over time.

Our study contributes to the literature by examining the interaction of economic complexity, green technology integration, and environmental sustainability in Saudi Arabia. Using sophisticated econometric methods, the results illuminate important dynamics, determinants shaping sustainable development. This section contrasts the findings of the study with what is already known in the literature, underscoring consensus, differences and new propositions.

5.1. Technological Integration and Environmental Sustainability

The study shows a robust positive impact of ICT goods exports on ecological footprint, suggesting that technology integration causes more consumption of resources and thus more environmental degradation. This finding is consistent with Alajmi (2022), which discusses the environmental costs of energy-consuming technologies in the industrial sector in Saudi Arabia. However, unlike previous studies, for example, Hassan et al. (2023) highlighting the power of eco-innovation in reducing environmental impact, this study finds that current technological exports are not yet contributing to sustainable outcomes. Therefore, policy efforts should focus on fostering green technologies to balance economic growth with environmental preservation.

5.2. Economic Complexity and Diversification

The results point out that economic complexity is a significant determinant of Saudi Arabia's economic diversification, which corroborates the findings of Caldarola et al. (2024), who highlight the role of complex industries in achieving sustainable growth. However, the negative effect of FDI on economic complexity, as found in this study, runs counter to the earlier work of Asiimwe and De Kock (2019), who argue that FDI is beneficial in promoting industrial sophistication. It might thus reflect the nature of the FDI inflows in Saudi Arabia, concentrated in relatively less complex industries. It follows then that attracting quality FDI targeting advanced industries remains an important means to achieve diversification set by Vision 2030.

5.3. Role of Foreign Direct Investment and Trade Openness

This duality of the role of trade openness, promoting ICT exports while hampering economic complexity temporarily, echoes findings by Roy (2016), who critiques globalization for its mixed impact on sustainable development. In a similar way, the findings in this study regarding FDI are consistent with Makasi and Govender (2015), who indicated that not all foreign investments result in positive economic impact. Nevertheless, these previous studies differ from this one in that empirical evidence has been given in the context of Saudi Arabia, underlining the strategic role of trade and investment policies.

5.4. Environmental Impact versus Economic Growth

While the study does not find a direct causal relationship between GDP per capita and the ecological footprint, it points out that other factors, such as economic complexity and technological integration, influence environmental outcomes. This finding contrasts with Chaaben et al. (2024), who argue that economic growth directly influences environmental degradation in Saudi Arabia. This is partly justified, with the apparent discrepancy arising because long-term dynamics was a focus of this study, and impacts related to short-term economic growth could not sustain longer.

5.5. Strategic Implications for Policy

Comparing the present research with existing literature underlines the need to have comprehensive policies that integrate technological advancement, economic diversification, and environmental sustainability. Although past research is dedicated to general strategies, such as promoting eco-efficiency and green growth, the paper offers specific policy recommendations for Saudi Arabia. Examples of such detailed policies are developing high-complexity industries, sustainable FDI, and investment in green technologies.

In a nutshell, this study provides valuable lessons that can be learned from the complex interrelationships between economic, technological, and environmental factors in Saudi Arabia. The comparison of the findings with the existing literature highlights some important areas where Saudi Arabia can further improve its sustainable development strategy. Future research should investigate the long-term impacts of policy interventions, especially in the development of green technology and high-complexity industries.

6. CONCLUSION

This study offers an in-depth analysis of the economic, environmental, and technological dynamics of Saudi Arabia from 1995 to 2023. It uses key indicators to understand the long-term trends and relationships among economic growth, technological integration, and environmental sustainability. The study reveals several important conclusions that provide valuable insights for policymakers.

Firstly, the analysis of the ecological footprint (ECOFP) highlights the significant influence of economic and technological variables, particularly the Economic Complexity Index (ECI) and the ICT sector. The results suggest that economic growth, as measured by GDP per capita, leads to an increased ecological footprint over the long term, reflecting the higher consumption patterns associated with wealthier economies. Trade, however, shows a dual role: in the short term, it reduces the ecological footprint, but over time, increased trade leads to greater environmental impacts due to factors such as transportation emissions. This underscores the challenge of balancing economic growth with environmental sustainability, where policies need to address the long-term consequences of economic expansion on natural resources.

In terms of technological integration, the research emphasizes the role of ICT exports and imports in shaping economic complexity (ECI). ICT exports, particularly those from the past two periods, play a crucial role in driving economic diversification, suggesting that Saudi Arabia's future economic growth will be heavily influenced by the expansion of its digital economy. Conversely, foreign direct investment (FDI) appears to have a negative effect on economic complexity, possibly due to investments that focus on less complex sectors. This points to the need for strategic management of FDI to align with the country's goal of diversifying its economic base. Furthermore, while trade positively impacts ICT exports, it negatively affects economic complexity in the short term, indicating that trade may not always contribute to the advancement of sophisticated industries.

Foreign direct investment (FDI) plays a significant role in the Saudi economy, with a complex relationship to various economic outcomes. The study finds that FDI is positively associated with short-term GDP growth and ICT exports, highlighting the importance of attracting foreign capital for technological advancement. However, the impact of FDI on economic complexity is mixed, suggesting that foreign investments may not always support the development of high-value industries. Additionally, the relationship between trade openness and FDI is nuanced, with trade showing a positive relationship with ICT exports, while its impact on economic complexity and environmental sustainability is less clear. Therefore, careful management of both trade and foreign investment is necessary to foster a diversified, high-tech economy while mitigating negative environmental effects.

The relationship between technological growth and environmental sustainability is another critical finding of the study. ICT exports and imports are closely linked to the ecological footprint, with increased technological integration resulting in higher resource consumption and environmental impact. While the ICT sector drives economic growth and diversification, its growth must be accompanied by sustainable policies to minimize the ecological consequences of rapid technological expansion. The study also highlights that while FDI can promote cleaner technologies, it is essential for foreign investments to support environmentally friendly industries to ensure long-term sustainability.

The Granger causality test results show that the ecological footprint influences several key variables, including economic complexity, ICT exports, ICT imports, FDI, and trade. However, no causal relationship was found between the ecological footprint and GDP per capita, suggesting that ecological outcomes are influenced by factors beyond economic growth. The impulse response function (IRF) analysis reinforces this view, revealing that while variables like ICT exports, ICT imports, FDI, and trade have short-term effects on the ecological footprint, their influence diminishes over time. This indicates that the environmental impact of economic and technological changes may be more transitory than initially expected.

In conclusion, the study emphasizes the complex interplay between economic growth, technological integration, and environmental sustainability in Saudi Arabia. It highlights the need for policies that promote economic diversification, particularly through the ICT sector, while also addressing the environmental challenges associated with this growth. The findings suggest that Saudi Arabia's path to sustainable development requires careful management of foreign investments, trade, and technological advancements to ensure that economic progress does not come at the cost of the environment. By fostering a more sophisticated and sustainable economy, Saudi Arabia can navigate the challenges of the 21st century and secure a prosperous, ecologically balanced future.

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