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HOW CAN THE MINING SECTOR DIVERSIFY THE SAUDI ECONOMY TO ACHIEVE ECO-EFFICIENCY?

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ABSTRACT: This paper explores how export diversification and the mining sector influence Eco-efficiency in Saudi Arabia, both in the short-run and long-run impacts. The paper also accounts for the influence of GDP, aggregate power usage, and urban development. Adopting an autoregressive distributed lag (ARDL) framework, the paper first confirms a stable long-run relationship among the variables under consideration. The results show that, in both the short and long run, increased trade diversification, GDP, and urban development lead to increased CO2 emissions. Notably, the negative impact of these variables on the environment is more pronounced in the long run. By contrast, investment in the mining sector is found to reduce CO2 emissions and improve the environment in both the short and long run. Unexpectedly, energy consumption has no significant environmental impact. The results are found to be robust under various statistical tests for common issues. Stability tests also support the robustness of the long-run relationships and validity of the ARDL model. The results of this study have significant implications for designing strategies for environmental conservation.

KEYWORDS: eco-efficiency, CO2 emissions, economic diversification, the mining sector, Saudi Arabia, ARDL

Introduction

Eco-efficiency is a long-term change in climate conditions over several years, usually several decades or even centuries. The changes are primarily caused by the emission of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Trenberth, 2018; Moiceanu & Dinca, 2021). GHGs retain heat in the Earth's atmosphere, causing global warming. With the exacerbation of effects of these events, both in terms of impact on health, economic performance, ecosystems, and social stability, the concerns for eco-efficiency and environmental degradation have attracted the focus of governments and international organisations.

Researchers continue to examine the forces of CO_2 emissions and eco-efficiency changes. Recent literature (Wang et al., 2019; Demena & Afesorgbor, 2020; Aller et al., 2021; Alharbey & Ben-Salha, 2024; Djedaiet et al., 2024) has examined the effects of numerous economic, demographic, and technological factors on growth in emissions. However, very little effort has been put into economic diversification and the mining sector as the drivers of environmental trends.

Economic diversification, particularly in oil and gas export-dependent countries, can be an effective tool for emission reduction. Transitioning from fossil fuel-hungry industries and investing in sectors such as clean energy, sustainable agriculture, and ecotourism can reduce carbon-intensive production and energy consumption reliance. Diversification encourages the use of renewable resources, such as solar and wind energy, and stimulates green technology innovation. These changes in structure can help reduce emissions and enhance eco-efficiency by facilitating more environmentally friendly production and consumption patterns.

In addition, investment in green sectors is also a focus on long-term sustainability. For example, countries diversifying their energy sector by incorporating solar, wind, or hydropower can reduce CO_2 emissions significantly and contribute to global climate goals, enhance energy security, and reduce the risk of exposure to insecure fossil fuel markets. Economic diversification fosters technical innovation, providing room for new emerging green technologies and increasing the ability of a country to adapt and respond to environmental change.

The mining industry has a twofold role in the situation. On the one hand, it can be supportive of sustainability if directed towards green initiatives, including mining raw materials for green energy infrastructure or investing in green technologies. Mining practices that are aligned with the best environmental practices, adopt cleaner technologies, and introduce sustainable practices can cut emissions and facilitate technology transfer from high- to low-income economies. These investments can enhance environmental performance and aid low-carbon development.

On the other hand, the mining sector can exacerbate environmental degradation when associated with emissions-based activities. Coal mining, heavy industry, deforestation, or widespread land degradation is accountable for the loss of biodiversity and elevated CO_2 emissions. Uncontrolled mining can jeopardise environmental goals, especially in resource-rich developing countries. The environmental impacts of such mining can be severe, particularly when coupled with poor regulation enforcement and inadequate public accountability.

Governments' policy actions firmly decide the role that the mining sector plays in addressing green goals. Governments can influence sustainability through the issuance of incentives, such as taxation rebates to invest in green investments, policymaking, and assistance in the development of eco-technology-related research and development. Setting environmental control standards and imposing compliance can lower the detrimental effects of mining but stimulate development and innovation. In conjunction with this, governments can help facilitate investment in green mining methodology for job creation, emission reduction, and economic growth.

Exploration of sustainable energy resources, such as rare earth minerals used in batteries or solar panels, can also initiate diversification. In the way that it contributes to GDP and creates jobs, sustainable mining can make sure that the dominance of fossil fuels on the economy is limited. This allows overall transition towards a low-carbon economy. Coupling development with environmental conservation is still an issue, however, especially for economies such as Saudi Arabia that are dependent on fossil fuel income.

Saudi Arabia provides a suitable case study for examining these dynamics. Saudi Arabia experienced stunning economic growth between 1980 and 2014 based on oil exports, but also faced mounting environmental pressures during the same period. The need to diversify its economy and develop

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its mining sector sustainably is at the core of its development agenda. Vision 2030, which is Saudi Arabia's strategic plan for economic reform, is heavily geared towards reducing dependence on oil and increasing investment in alternative industries like mining and renewables.

This study explores how can the mining sector can diversify the Saudi economy to achieve Eco-efficiency in Saudi Arabia during 1980–2020. The aim is to add empirical evidence to the extent to which these drivers affect environmental sustainability. Understanding this relationship will be crucial to developing effective policy interventions that ensure economic growth without compromising the environment. The study investigates both short- and long-term effects of diversification and mining on emissions, where areas of potential policy intervention and planning strategies are identified.

The relevance of this study is that it addresses two not-so-well-researched topics – economic diversification and mining – and their environmental consequences. It adds to the body of literature by plugging in a knowledge gap in studies that examine how these factors interplay with eco-efficiency and CO_2 emissions, especially in oil-based economies. The research will guide Saudi Arabia's future development plans, emphasising the trade-offs and synergies in achieving growth and sustainability.

Furthermore, under growing worldwide climatic pressures, countries must fit into new environmental and economic realities. As a player in world energy markets, Saudi Arabia owes it to itself to lead a change in that direction. Truly making significant achievements in diversification of the economy and green mining will enhance the resilience of the country, avoid environmental risks, and support global efforts in slowing down climate change.

This paper is organised as follows: Section 2 is a literature review. Section 3 presents the methodology and the data sources. Section 4 presents empirical results. Section 5 concludes with main findings and policy implications.

Previous Research Overview

This paper examines the relationship between economic diversification, the mining sector, and CO2 emissions in Saudi Arabia. The existing literature emphasises the role played by diversification in curbing environmental risks, especially in GCC countries, which are natural resource-reliant economies. Literature either focuses on the effects of diversification on emissions or the environmental fallout of mining activities.

There is literature on the environmental impact of economic diversity. Economic diversification has a dual impact on environmental sustainability. On one hand, diversification that is directed into renewable energy and green industries lowers carbon emissions and supports sustainable development. On the other hand, diversification of exports has the potential to increase production and energy use, which can increase emissions over the long term (Shi et al., 2023).

Empirical evidence on this question is mixed. Apergis et al. (2018), by using ARDL and panel quantile specifications for 1962–2010 data for 19 developed countries, confirmed that higher export product concentration is linked to lower CO_2 emissions. Similarly, Shahzad et al. (2020), on the basis of 1971–2014 data for both developed and developing countries, showed that export diversification lowers CO2 emissions globally. Specifically, a 1% increase in diversification lowers emissions by 0.334% in the world, 0.247% in developed nations, and 0.236% in developing nations.

Can et al. (2020) used ARDL bounds, DOLS, and FMOLS on 84 developing nations. They confirm that export diversification reduces emissions but only in the long term. In contrast, Toktaş (2021) found that export diversification in Poland (1990–2015) increases emissions, worsening environmental quality.

At the regional level, Shi et al. (2023) used FGLS, FE, and panel threshold methods on China and found that export diversification reduces CO2 emissions across different regions. Dou et al. (2023) also reached the same findings when they took into account sulfur dioxide emissions. Finally, Lieu and Ngoc (2023) estimated the impact of economic diversification and FDI on five Asian countries and found that diversification lowers emissions, whereas FDI is environmentally neutral.

These studies suggest that the environmental impact of economic diversification is region, method, and focus dependent and thus can harm as well as enhance environmental quality depending on context and use.

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Literature on mining industry's environmental impacts compiles the most prominent among them. Mineral resources can promote economic growth through providing crucial raw materials to industries, generating state revenues, and supporting secondary activities such as equipment supply and repair (Huang et al., 2017). Such avenues encapsulate the extent in which mining presents itself to create more extensive economic opportunities, especially in less developed economies.

However, other points of view argue that reliance on mineral resources can be detrimental to long-term growth. Early theorists like America (1950) and Singer (1975) identified the terms-of-trade deterioration: countries that trade raw minerals may face declining export prices but with rising import prices for manufactured goods, reducing their trade balance and potential for growth (Davis & Tilton, 2008). The Dutch disease also refers to the manner in which a resource-based economy would experience overconcentration in the mining sector, discouraging economic diversification and increasing vulnerability to shocks. Further, depletion of resources creates long-term issues since mineral resources are non-renewable, limiting future growth (Cowell et al., 1999).

There is empirical evidence on both sides. Stern (1995), using 19 mineral-exporting countries between 1963 and 1988, found the long-term benefits of mining are not unconditional. Sala-i-Martin et al. (2004), using Bayesian Averaging of Classical Estimates for 88 countries, showed that mining can contribute to GDP growth under specific circumstances. In America, Douglas and Walker (2017) studied 409 counties between 1970 and 2010 and found that one standard deviation increase in mining dependence lowered per capita income growth by 0.2% in the short term and 0.5% in the long term.

Other studies point to possible benefits where mining revenues are utilised effectively. Sangare and Maisonnave (2018) proved that in Niger, mining rents would improve infrastructure and employment. In Saudi Arabia, Zmami et al. (2021) confirmed that mining promotes economic and social sustainability in the short and long term. The findings show mining's contribution varies with national policies and resource management strategies.

Methods And Data Description

Dataset Overview

This study investigates how can the mining sector diversify the Saudi economy to achieve Eco-efficiency in Saudi Arabia during 1980–2020 and the indicator for the environment being represented by CO_2 emissions, which include CO_2, CH_4, N_2O, and F-gases. Larger emissions provide a better indicator of environmental harm. The data on CO_2 emissions have been obtained from Climate Watch. The diversification of the economy is captured by export diversification, as a function of the number and variety of products exported, from IMF data. The mining industry is measured by its net inflows as a percentage of GDP, from World Bank data. The data includes three control variables: GDP per capita, urbanisation, and total energy consumption (see Table 1).

Table 1. Variable Description

Proxy	Indicators	Origin
lnCO2	CO2 emissions	Climate Watch
lnED	Export diversification	International Monetary Fund
lnMS	Mineral rents (% of GDP)	World Development Indicators
lnGDP	Gross Domestic Product (constant 2015 US$)	World Development Indicators
lnULA	Urban land area (sq. km)	World Development Indicators
lnPECpc	Primary Energy Consumption per capita	Energy Institute

The Figure 1 presents the natural logarithms of CO_2 emissions ($LnCO_2$), export diversification (LnED), and mineral rents as a share of GDP (LnMR) for Saudi Arabia between 1980 and 2020. Where the missing values were filled for the export diversification variable (ED) for the period 2015–2020, and for the mineral rents variable (MR) for the period 1980–1988. $LnCO_2$ and LnED were relatively

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stable. LnED fell slightly in the 1980s, then gradually increased, reflecting modest export diversification gains. $LnCO_2$ has a gentle U-shaped trend, with emissions falling until the mid-1990s, then gradually increasing.

LnMR is very volatile. It declined sharply from 1998-2003 to below zero on a long scale, indicating very low rents from minerals as a proportion of GDP. This also fits the slump in the international oil price in the late 1990s. From 2004, LnMR recovered and continued to rise to around 2012, indicating increased mineral rent incomes. Volatility still occurred, maybe due to uncertainty in oil markets and changing levels of production. The graph suggests a weak correlation of CO_2 emissions with mineral rents, and little export diversification progress during the period.

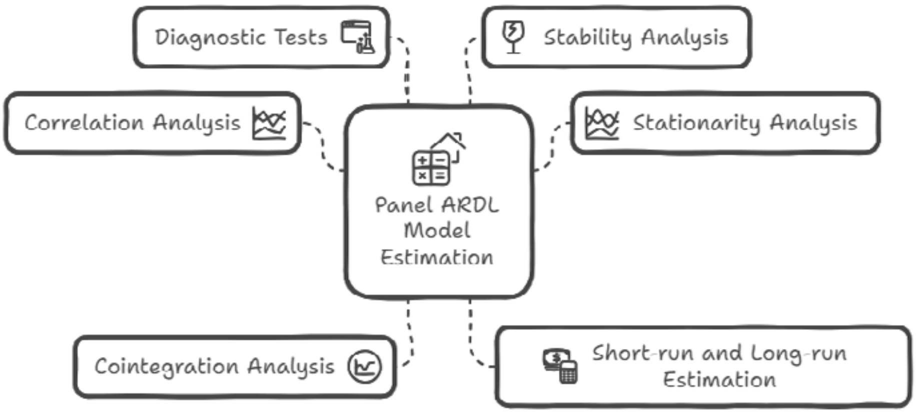

Figure 1. Change in CO2, ED and MR in Saudia during 1980-2020

Research Approach

The research explores the effect of economic diversification and the mining sector on Eco-efficiency in Saudi Arabia. The autoregressive distributed lag (ARDL) approach is applied to quantify short- and long-run impacts. Figure 2 illustrates the empirical model.

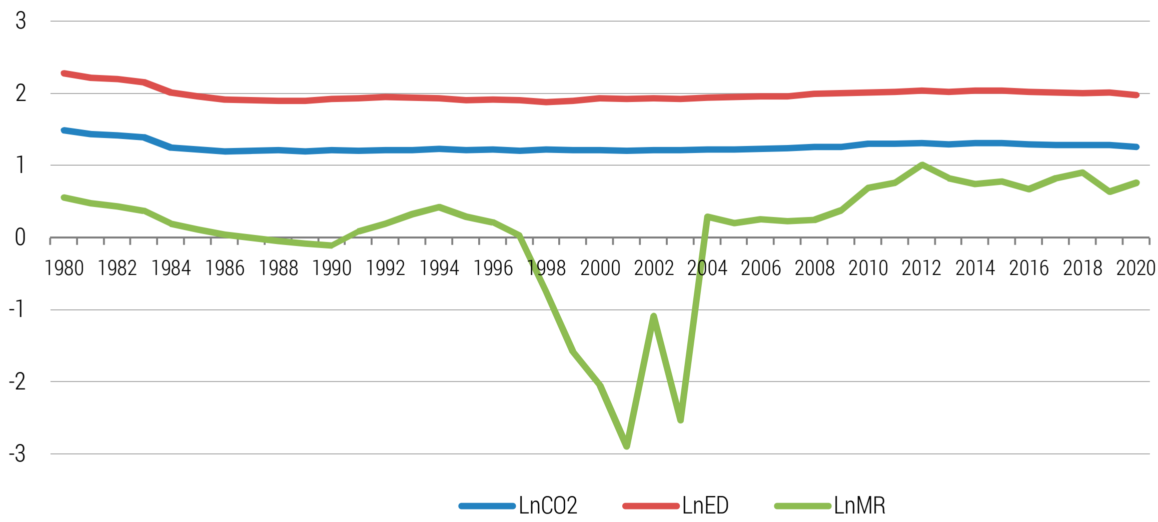

Figure 2. ARDL Model Estimation Process

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The variables examined in this study can be expressed mathematically as follows:

$$lnCO2_t = \alpha_0 + \alpha_1 lnED + \alpha_2 lnMR + \alpha_3 lnGDP + \alpha_4 lnPU + \alpha_{51} lnPECpc + \epsilon_t, \quad (1)$$

In this, (CO_2) represents carbon dioxide emissions, (ED) represents export diversification, (MR) represents activity of the mining sector, (GDP) represents gross domestic product, (PU) represents urbanization, and (PECpc) represents per capita energy consumption.

The long-run relationships among the variables are estimated using the following equation:

$$lnCO2_t = \alpha_0 + \sum_{n=1}^{p} \beta_n \, lnCO2_{t-n} + \sum_{m=1}^{q1} \gamma_m \, lnED_{t-m} + \sum_{j=1}^{q2} \rho_j \, lnMR_{t-j} + \sum_{s=1}^{q3} \vartheta_s \, lnGDP_{t-s} + \sum_{k=1}^{q4} \theta_k \, lnPU_{t-k} + \sum_{h=1}^{q5} \tau_h \, lnPECpc_{t-h} + \omega_t, \quad 2)$$

And finally, the immediate or short-run impacts are represented by the following equation:

$$\Delta(lnCO2_t) = \alpha_0 + \sum_{n=1}^{p} \beta_n \, \Delta(lnCO2_{t-n}) + \sum_{m=1}^{q1} \gamma_m \Delta(lnED_{t-m}) + \sum_{j=1}^{q2} \rho_j \, \Delta(lnMR_{t-j)} + \sum_{s=1}^{q3} \vartheta_s \, \Delta(lnGDP_{t-s}) + \sum_{k=1}^{q4} \theta_k \Delta(lnPU_{t-k}) + \sum_{h=1}^{q5} \tau_h \, \Delta(lnPECpc_{t-h}) + \rho_{t-1} + \varepsilon_t. \quad (3)$$

where: $\rho t{-}1$ is Error correction term lagged by one period and εt is error term in period.

Key Analytical Findings

Statistics Descriptive

The variables have moderate scatter. LnMR is most unstable and has the lowest mean and highest variability, i.e., instability in mining. LnGDP and LnUP are stable and have small ranges. All variables are log-transformed and on the basis of 41 observations, enabling valid summary statistics (see Table 2).

Table 2. Statistics Descriptive

	LnCO2	LnED	LnMR	LnGDP	LnUP	LnPECpc
Mean	1.262	0.722	-1.915	11.593	7.092	2.382
Median	1.232	0.724	-1.738	11.548	7.111	2.356
Max	1.492	0.786	-1.032	11.856	7.424	2.534
Min	1.197	0.653	-4.816	11.364	6.6	2.172
Obs	41					

Interrelationships Among Variables

We start the empirical investigation by looking at the correlation between the variables of interest. The findings are given in Table 3. The correlation matrix shows a strong positive correlation between CO_2 and export diversification (0.705). Mineral rents weakly correlate with CO_2 (0.345) and GDP (0.358). GDP strongly correlates with population (0.88) and energy consumption per capita (0.867), suggesting economic growth is to blame. Per capita energy consumption and population are also highly correlated (0.948). Negative correlations of export diversification with population (–0.319) and energy consumption (–0.233) could indicate structural change in the intensity of energy and demographic implications.

Table 3. Interrelationships Among Variables

	LnCO2	LnED	LnMR	LnGDP	LnUP	LnPECpc
LnCO2	1					
LnED	0.705	1				
LnMR	0.345	0.236	1			
LnGDP	0.284	0.055	0.358	1		
LnUP	-0.172	-0.319	0.167	0.88	1	
LnPECpc	-0.095	-0.233	0.313	0.867	0.948	1

Time Series Stability Check

In order to describe the impact of export diversification and mining on CO_2 emissions, one needs to initially test whether the variables are unit-rooted. This study employed two strong unit root tests. We initially used the ADF test developed by Elliott et al. (1996). Secondly, we have used the PP test of Phillips and Perron (1988) which is the benefit of being able to account for potential structural breaks in the variables. The outcomes of these tests appear in Table 4.

Table 4. ADF and PP Test Outcomes

Variables	ADF		PP	
	level	1st dif	level	1st dif
LnCO2	-3.672	-	-3.831	-
LnED	-2.727	-5.758***	-2.756	-5.760***
LnMR	-2.216	-9.606***	-2.452	-8.998***
LnGDP	0.847	-3.652***	0.211	-3.678***
LnUP	-6.806***	-	-6.296***	-
LnPECpc	-2.584	-2.392***	-2.442	-6.412***

***, **, and * indicate rejection of the unit root null hypothesis at the 1% significance level.

The outcomes of the unit root tests reveal that LnCO2 and LnUP are level stationary based on both ADF and PP tests. LnED, LnMR, LnGDP, and LnPECpc are not level stationary but become stationary upon first differencing, that is, they are integrated of order one, I(1). The strong rejection of the null hypothesis at the 1% level for these differenced variables reaffirms stationarity after transformation. These hybrid orders of integration (I(0) and I(1)) are suitable for an ARDL model, which can handle both. The result establishes the possibility of further exploring long-run and short-run relationships among the variables.

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Evaluation of Long-Run Linkages

The ARDL bounds test approach is employed to test for the presence of a long-run cointegration relationship. For robustness, both the F-statistic and t-statistic are estimated. The results are presented in Table 5.

Table 5. ARDL Cointegration Test Output

	Model	conclusion
F-statistics	3.908***	
Lower-upper bound (10%)	2.08 – 3.00	Co-integration
Lower-upper bound (5%)	2.39 – 3.38	
Lower-upper bound (1%)	3.06 – 4.15	
K	5	

* indicates significance at the 1% level.
** indicates significance at the 5% level.
*** indicates significance at the 10% level.
K refers to the number of regressors in the model.

The ARDL bounds test result shows an F-statistic of 3.908, which is higher than the 10% and 5% upper bounds and slightly lower than the 1% upper bound. This shows strong evidence of a long-run cointegration relationship between the variables at the 10% and 5% levels of significance. With K = 5 regressors, the model meets the required conditions for applying the bounds test. 10% level of statistical significance (***) is a confirmation of a long-run valid relationship. The results confirm the presence of a long-run stable equilibrium relationship among the selected explanatory variables and the model's dependent variable.

Estimation of Temporal Effects

With the confirmed cointegration, the ARDL model is employed to estimate the impact of various variables on CO_2 emissions. Table 6 provides the estimated short-run and long-run coefficients. The error correction term (ECT) is negative and significant at the 1% level, confirming the evidence of cointegration provided in Table 5. The ECT estimate of -0.78 indicates the high speed of adjustment, and 78% of the short-run deviations are adjusted within a year. The long-run estimates indicate that export diversification has a negative and statistically significant coefficient of 0.484, indicating its mitigating effect on CO_2 emissions in the long run.

Table 6. Model Output Summary

	Long- term		Short- term	
	Parameter	Standard error	Parameter	Standard error
ECT	-	-	-0.780***	0.239
LnED	-0.484***	0.283	-0.454***	0.247
LnMR	0.003**	0.005	-1.820*	2.352
LnGDP	0.917*	0.226	2.026***	1.413
LnUP	-0.415**	0.123	-1.235	1.306
LnPECpc	0.322***	0.340	1.726**	0.212
C	-5.293	1.447	-4.854	1.488

***, **, and * indicate that the coefficients are statistically significant at the 1%, 5%, and 10% levels, respectively.

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Table 6 reports the ARDL model estimates of both short- and long-run effects on CO_2 emissions. The error correction term (ECT) is negative and statistically significant at the 1% level with a coefficient of -0.780. This confirms the existence of a long-run equilibrium relationship and suggests that 78% of short-run deviations from long-run equilibrium are adjusted within a year.

Export diversification (LnED) also features statistically significant coefficients that are negative both in the long run (-0.484) and short run (-0.454). This reveals that CO_2 emissions fall by 0.484% in the long run and 0.454% in the short run due to a rise in export diversification by 1%. The results suggest that trade diversification improves ecological well-being in both time horizons, with the impact being more severe in the long run.

Mining sector inflows (LnMR) reveal mixed findings. In the long run, the coefficient is positive (0.003) and significant at the 5% level, pointing towards a slight increase in emissions. In the short run, however, the coefficient is negative (-1.820) and significant at the 10% level. One can deduce that mining sector activity can reduce emissions in the short run, possibly because cleaner technologies are being used or there are stricter regulations at early development stages.

GDP per capita (LnGDP) has a positive relationship with CO_2 emissions in both time periods. The long-run coefficient is 0.917 and significant at the 10% level, while the short-run coefficient is 2.026 and significant at the 1% level. This indicates that economic growth in Saudi Arabia is still resulting in higher emissions, especially in the short run.

Urbanisation (LnUP) has a statistically significant negative coefficient in the long run (-0.415), which suggests that urban development can produce emissions savings in the long term, possibly because of improved infrastructure or energy efficiency. Its short-run coefficient (-1.235) is not statistically significant, and thus there is no short-run impact on emissions.

Per capita energy consumption (LnPECpc) positively and significantly impacts the long run (0.322) and short run (1.726), showing that energy increments are highly associated with rising emissions. The stronger short-run effect reflects the environmental cost in the short term of higher energy demand.

Overall, the results show that while some variables such as export diversification and urbanisation, reduce emissions, others such as GDP and energy consumption increase environmental degradation. The combined effects of the mining industry point to the necessity of policy focus on clean production technologies.

Model Accuracy Assessment

Table 7 presents the results of tests for robustness validation of the model. The Breusch-Godfrey test shows no serial correlation (p = 0.343). The ARCH test shows no heteroskedasticity (p = 0.176), implying constant error variance. However, the Jarque-Bera test rejects normality (p = 0.003), suggesting that residuals are not normally distributed.

Table 7. Robustness Validation

Test	Statistic	p-value
Breusch-Godfrey Serial Correlation LM test	1.113	0.343
Heteroskedasticity Test ARCH	1.903	0.176
Jarque-Bera normality test	11.198	0.003
Ramsey RESET test	11.586	0.002

The Ramsey RESET test reveals model misspecification (p = 0.002) and implies that there are missing relevant variables or nonlinear terms. Despite the absence of serial correlation and heteroskedasticity, the model should be further refined regarding its specification to manage normality and functional form issues.

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Testing Model Consistency Over Time

Brown et al.'s (1975) CUSUM and CUSUM of squares tests are used to test the stability of the long-run coefficients of the ARDL model. Figure 3 presents the results of both tests. The graphs indicate that the long-run parameters are stable over time.

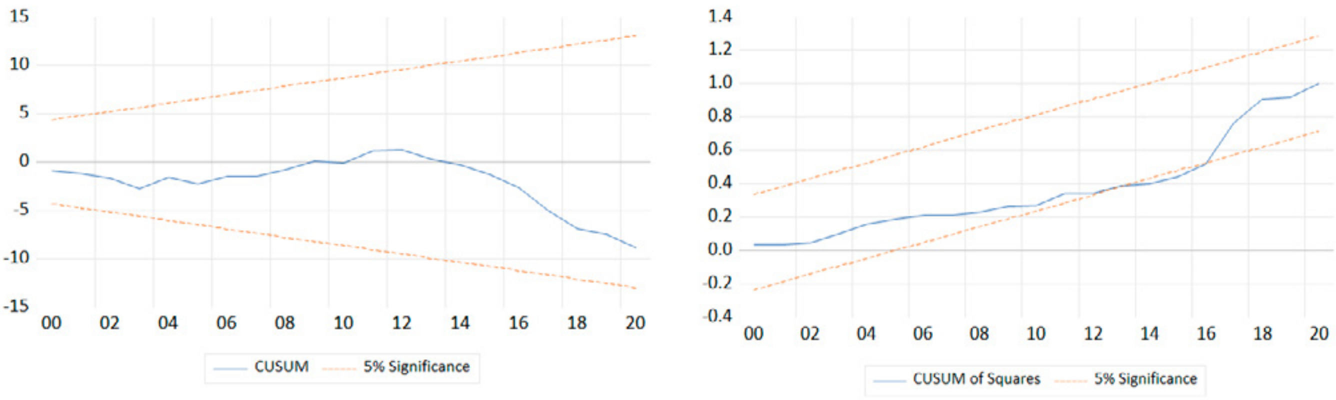

Figure 3. Evaluation of Long-Term Model Consistency

Conclusion and Final Observations

Although Eco-efficiency in GCC countries has attracted increasingly more academic attention, relatively little research has focused on the direct roles of export diversification and the mining sector. This study fills some of that gap by analysing their impact on Saudi Arabian CO_2 emissions from 1980 to 2014. Using the ARDL approach, the findings confirm a long-run equilibrium relationship between CO_2 emissions and key economic variables: export diversification, mining production, GDP, power usage, and urban development.

The results show that trade diversification, urbanisation, and GDP exert statistically significant positive effects on CO_2 emissions both in the short and long run. Notably, long-run impacts are bigger, which means economic transformation and population pressure may make environmental issues worse in the long term. In contrast, the mining industry is related to emission decrease, which means green investment and green mining activities can help improve environmental performance. Energy use, however, shows no significant impact, possibly due to Saudi Arabia's high reliance on fossil fuel, coupled with little variation in energy efficiency over the period of study.

Policy recommendations include:

- Cleaner technologies and environmental policy promotion in export industries.
- Sustainable mining practices promotion, especially for green economy strategic minerals.
- Green urban planning for curbing emissions from expanding cities.
- Prioritizing the growth of renewable energy and energy efficiency reforms to reduce dependency on carbon fuels.
- Aligning national development plans with climate goals in Vision 2030.

Subsequent studies may utilize sectoral data and examine trends from 2014 and beyond, including the impacts of environmental regulation, energy reforms, and industrial policy reforms. The scope of analysis to other GCC nations may offer a comparative perspective and promote regional policy coordination.

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The contribution of the authors

Conceptual framework development, B.L and S.R.; the comprehensive review of pertinent literature, S.R. and B.L.; the methodological approach, B.L.; formal analytical procedures, B.L. and S.R.; the writing of the manuscript, B.L and S.R.; the conclusions and discussion, B.L. and S.R.

The authors have perused and consented to the final published iteration of the manuscript.

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