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Water stress, agricultural efficiency, energy use, and CO_2 emissions: Evidence from GCC countries

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Research Article

Keywords: Freshwater scarcity, Water productivity, Fossil fuel dependence, Carbon intensity, Panel econometric modeling

Posted Date: February 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8844668/v1

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Additional Declarations: No competing interests reported.

Abstract

This study examines the long-run and short-run relationships between water stress, agricultural efficiency, energy use, and CO_2 emissions in six GCC countries over the period 1992–2023. Using second-generation panel econometric techniques that account for cross-sectional dependence and heterogeneity, the analysis applies the Westerlund cointegration test, the Common Correlated Effects Mean Group (CCE-MG) estimator, and an error-correction causality model (ECM). The results confirm a stable long-run equilibrium among the variables. Energy use emerges as the dominant explanatory factor, exerting a positive and statistically significant effect on CO_2 emissions in both the long run and the short run. Water stress significantly affects emissions in the long run, indicating that persistent pressure on freshwater resources influences environmental outcomes through gradual structural and technological adjustment rather than immediate short-run changes. In contrast, agricultural efficiency does not exhibit a statistically significant effect on emissions, suggesting that improvements in water productivity have not translated into measurable emission reductions at the macro level. Robustness checks using alternative lag specifications and Dumitrescu–Hurlin panel Granger causality tests confirm the stability of these conclusions. Overall, the findings highlight the central role of energy dynamics and the long-run environmental implications of water scarcity in GCC economies.

1. Introduction

Water scarcity is one of the most binding constraints on agricultural sustainability in arid and semi-arid regions. In the Gulf Cooperation Council (GCC) countries, renewable freshwater resources are extremely limited, rainfall is scarce and irregular, and evapotranspiration rates are high. Despite agriculture contributing a modest share to gross domestic product, it accounts for a disproportionately large share of total freshwater withdrawals and remains strategically important for food security and rural stability. Ensuring the long-term viability of agricultural production in such environments therefore requires careful management of water resources, energy inputs, and environmental impacts. At the same time, GCC economies are characterized by energy-intensive growth patterns and fossil fuel–based production systems, which have resulted in high levels of carbon dioxide (CO_2) emissions (Wada et al., 2012; FAO, 2017; Legg, 2021).

In water-scarce economies, agriculture, water management, and energy systems are structurally interconnected. The water–energy–agriculture–environment nexus framework emphasizes that water extraction, irrigation, desalination, and groundwater pumping require substantial energy inputs. When energy systems rely heavily on fossil fuels, these processes may increase environmental pressure through higher emissions (Mekonnen & Hoekstra, 2011; Dalin et al., 2017). In the GCC region, desalination plants and deep groundwater abstraction play a critical role in sustaining domestic and agricultural water supply. These technologies are often energy-intensive and, in many cases, powered by carbon-based energy sources. As a result, water scarcity may indirectly affect environmental outcomes by increasing the energy intensity of water provision (Wada et al., 2017; Liu et al., 2017).

1.1 Water Stress and Environmental Pressure

Water stress, typically measured as the ratio of freshwater withdrawals to renewable freshwater availability, captures the intensity of pressure exerted on national water systems. In highly water-stressed environments, additional water supply increasingly depends on technological and energy-intensive adaptation strategies. Empirical studies demonstrate that unsustainable water withdrawal patterns can amplify environmental risks and increase reliance on energy-intensive infrastructure (Mekonnen & Hoekstra, 2011; Wada et al., 2012). International assessments further highlight the close interdependence between water security and climate mitigation, particularly in arid regions where adaptation frequently relies on carbon-intensive technologies (FAO, 2017; Legg, 2021).

From an applied agricultural perspective, persistent water stress may alter cropping patterns, irrigation methods, and resource allocation decisions. Farmers may adopt deeper groundwater extraction, invest in desalinated water, or shift to water-saving technologies, all of which carry energy implications. These structural adjustments may not produce immediate changes in emissions but can influence environmental pressure over the long run. Despite the theoretical relevance of water stress, relatively few empirical studies explicitly incorporate direct water stress indicators when modeling CO_2 emissions in GCC countries.

Given the structural linkages between water scarcity, energy demand, and environmental outcomes, this study proposes the following hypothesis:

H1. Water stress has a significant effect on CO_2 emissions in GCC countries.

This hypothesis does not impose a priori the direction of the effect, as the net outcome may reflect competing mechanisms: increased energy use for water supply versus long-run structural adjustment toward more efficient resource allocation.

1.2 Agricultural Efficiency and Emissions

Improving agricultural efficiency-often proxied by water productivity-has become a central pillar of sustainability strategies in water-scarce regions. Water productivity reflects the economic value generated per unit of water used in agricultural production (Zwart et al., 2010; FAO, 2020). In theory, higher water productivity reduces water withdrawals and the associated energy required for pumping and irrigation. Modern irrigation technologies, improved soil management, and precision agriculture are widely promoted to enhance efficiency and reduce resource intensity (Wang et al., 2016).

However, theoretical and empirical studies caution against assuming a straightforward environmental benefit. Efficiency improvements may reduce production costs and stimulate agricultural expansion, leading to rebound effects that offset water and energy savings (Thenkabail, 2008; Chandio et al., 2020; Ahmed et al., 2020). In the GCC context, agriculture remains relatively small in economic size but highly dependent on irrigation and energy-intensive water supply systems. Consequently, efficiency gains may improve local water management without necessarily producing measurable reductions in aggregate CO_2 emissions at the macroeconomic level.

Given that efficiency-oriented policies are designed to reduce resource intensity and support long-term sustainability, the following hypothesis is advanced:

H2. Higher agricultural efficiency reduces CO_2 emissions in GCC countries.

Testing this hypothesis allows us to assess whether improvements in water productivity translate into broader environmental benefits or whether scale effects limit their aggregate impact.

1.3. Energy Use and CO_2 Emissions

Among the components of the nexus, energy use represents the most direct and well-established driver of CO_2 emissions. In fossil fuel–based economies, increases in energy consumption tend to translate almost mechanically into higher emissions unless accompanied by significant decarbonization (Sadorsky, 2012; Omri, 2014; Al-Mulali & Ozturk, 2016). In the GCC, energy demand is reinforced by industrial production, climatic cooling requirements, desalination, and water pumping systems, creating a strong structural linkage between energy use and environmental pressure.

Empirical studies consistently identify energy consumption as a primary determinant of emissions in resource-dependent and Middle Eastern economies (Shahbaz et al., 2013; Acheampong et al., 2019; Nathaniel et al., 2021). Given the central role of energy in both agricultural production systems and water infrastructure, energy use is expected to exert both short-run and long-run effects on emissions.

Accordingly, the third hypothesis is formulated as follows:

H3. Energy use has a positive effect on CO_2 emissions in GCC countries.

This hypothesis reflects the expectation that energy-driven dynamics dominate short-run emission changes and remain a key determinant of long-run environmental outcomes in fossil fuel–based economies.

Although prior research has examined selected elements of the water–energy–environment nexus, important gaps remain. Few studies integrate direct measures of water stress and agricultural efficiency within a unified empirical framework applied specifically to GCC countries. Moreover, limited attention has been given to distinguishing between short-run dynamics and long-run structural adjustment in the regional agricultural sustainability context.

To address these gaps, this study pursues three main objectives:

- To examine whether a stable long-run equilibrium relationship exists among water stress, agricultural efficiency, energy use, and CO_2 emissions in GCC countries.
- To estimate the long-run elasticities and short-run dynamics linking these variables while accounting for cross-sectional dependence and country heterogeneity.
- To clarify whether environmental pressure in GCC economies is primarily driven by energy-related short-run mechanisms or by longer-term structural adjustments associated with water scarcity and agricultural resource use.

By providing region-specific empirical evidence from one of the world's most water-constrained areas, this study contributes to applied agricultural sustainability research and offers policy-relevant insights for improving water productivity while mitigating environmental pressure in arid economies.

The next section outlines the empirical framework and model specification used to assess the hypothesis.

2. Data and Methodology

This section outlines the data, variables, and econometric methods employed to analyze the relationships among water stress, agricultural efficiency, energy use, and CO_2 emissions in GCC countries.

2.1. Data

This study employs an annual unbalanced panel of six GCC countries, Saudi Arabia, Bahrain, Kuwait, Oman, Qatar, and the United Arab Emirates, over the period 1992–2023. All variables are obtained from the World Development Indicators (WDI). The dataset is constructed at the country-year level, and the empirical analysis is conducted using annual observations.

The variables are defined in the following Table1:

Table 1
Variables Description

Variable	Symbol	Definition
CO_2 emissions	CO2	Amount of carbon dioxide released into the atmosphere per person from energy use, industry, agriculture, and waste.
Water stress	WS	Degree of pressure on freshwater resources, measured as the share of total water withdrawals relative to available renewable water.
Agricultural efficiency (water productivity)	AE	Economic value created from agriculture per unit of water withdrawn, indicating how efficiently water is used in production.
Energy use	EN	Amount of energy consumed to produce economic output, reflecting how energy-intensive the economy is.
Economic activity	GDP	Average income level measured by real gross domestic product per person.
Agriculture value added	AGR	Share of national output generated by agriculture, forestry, and fishing activities.

Environmental pressure is measured by CO_2 emissions. The key explanatory variables are water stress WS (freshwater withdrawals as a share of available renewable freshwater resources), agricultural efficiency AE, proxied by water productivity, and energy use EN measured as energy consumption. To control for macroeconomic conditions and production structure, the model includes GDP per capita (constant 2015 US$) and agriculture, forestry, and fishing value added AGR. All variables are expressed in natural logarithms to reduce scale effects and allow elasticity-based interpretation of coefficients.

2.2 Methodology

This study employs a second-generation panel econometric framework to examine the long-run and short-run relationships between water stress, agricultural efficiency, energy use, and CO_2 emissions in GCC countries over the period 1992–2023. The

analysis begins with cross-sectional dependence tests, followed by second-generation panel unit root tests that allow for heterogeneity and unobserved common shocks. Long-run cointegration among the variables is then assessed using the Westerlund (2007) error-correction-based panel cointegration test. Long-run elasticities are estimated using the Common Correlated Effects Mean Group (CCE-MG) estimator, which controls for unobserved common factors and permits country-specific slope coefficients. Finally, short-run and long-run causal relationships are examined using an error-correction-based causality model (ECM), where short-run effects are captured through differenced terms and long-run adjustment is captured by the significance of the error-correction term. As robustness checks, the ECM causality analysis is re-estimated using a two-lag specification to test sensitivity to lag length, and Dumitrescu–Hurlin panel Granger causality tests are applied to provide complementary evidence on short-run predictive causality across countries.

2.3. Baseline panel model specification

To examine the long-run and short-run interactions between water stress, agricultural efficiency, energy use, and environmental pressure in GCC countries, we specify the following baseline panel model:

$$\ln CO2_{it} = \alpha_i + \beta_1 \ln WS_{it} + \beta_2 \ln AE_{it} + \beta_3 \ln EN_{it} + \beta_4 \ln GDP_{it} + \beta_5 \ln AGR_{it} + \epsilon_{it}$$

where i denotes country ($i = 1, \ldots, 6$) and t denotes time (t = 1992,…2023).

α_i captures country-specific fixed effects, and ε_i is the error term.

The dependent variable, ln CO2, represents carbon dioxide emissions per capita and serves as a proxy for environmental pressure. WS denotes water stress, measured as freshwater withdrawals relative to available renewable freshwater resources. AE represents agricultural efficiency proxied by water productivity (Economic value per cubic meter of freshwater withdrawal). EN captures energy use, measured as energy consumption per unit of economic output. GDP denotes economic activity, proxied by GDP per capita, while AGR reflects agricultural structure, measured as agriculture, forestry, and fishing value added as a share of GDP.

3. Data Characteristics and Preliminary Econometric Tests

This section reports descriptive statistics and correlation analysis, followed by tests for cross-sectional dependence and panel unit roots to assess the time-series properties of the variables and to motivate the use of second-generation panel econometric methods.

3.1. Descriptive statistics

Table 2 reports the descriptive statistics for the main variables used in the analysis, including the mean, standard deviation, minimum and maximum values.

Table 2
Descriptive statistics

Variable	Mean	Std. Dev.	Minimum	Maximum
CO2	26.274246	10.791511	9.376252	53.599259
WS	948.243376	972.917389	84.714286	3850.5
AE	143.605694	152.256273	17.628081	683.632243
EN	147.823522	41.659622	73.350353	234.487167
GDP	34507.82111	16128.39386	17347.29113	81608.40807
AGR	1.423535	1.43429	0.094254	6.140717

The descriptive statistics indicate substantial heterogeneity across GCC countries and over time. CO_2 emissions, water stress, and agricultural efficiency exhibit wide dispersion, reflecting pronounced differences in environmental pressure, freshwater

scarcity, and resource-use efficiency within the region. Energy use shows relatively more stability, consistent with the structurally energy-intensive nature of GCC economies. GDP per capita varies considerably, capturing differences in economic scale, while agriculture value added remains modest, highlighting the limited but relevant role of agriculture in the regional economic structure. These patterns justify the use of econometric methods that allow for heterogeneity and non-constant variance across observations.

3.2.Multicollinearity tests

Table 3 presents the correlation matrix, which help to explore the relationships among variables and to assess potential multicollinearity issues.

Table 3
Correlation analysis

	CO2	WS	AE	EN	GDP	AGR
CO2	1					
WS	-0.0365	1				
AE	0.7241	0.0066	1			
EN	0.4491	-0.118	0.1214	1		
GDP	0.7993	0.1292	0.7061	-0.0674	1	
AGR	-0.5489	-0.1912	-0.5625	-0.5411	-0.3994	1

The correlation matrix shows that pairwise correlations among the explanatory variables remain within acceptable ranges and do not indicate severe multicollinearity. Importantly, correlations among the main explanatory variables are relatively low, with water stress showing negligible correlation with agricultural efficiency (0.007) and a weak association with energy use (-0.118), while the correlation between agricultural efficiency and energy use remains modest (0.121). The highest correlations are observed between CO_2 emissions and GDP (0.799) and between CO_2 emissions and agricultural efficiency (0.724), reflecting expected scale and productivity effects rather than mechanical collinearity. Overall, these patterns suggest that the explanatory variables capture distinct aspects of the water–energy–agriculture nexus, and multicollinearity is unlikely to bias the estimated coefficients.

Before proceeding with panel unit root and cointegration analysis, it is necessary to examine whether cross-sectional dependence exists among the GCC countries.

3.3. Cross-sectional dependence tests

The following table reports the results of the cross-sectional dependence tests.

Table 4
Cross-sectional dependence tests

Variable	N	Pairs	Avg overlap (T)	Pesaran CD	p-value (CD)	BP-LM	p-value (LM)	Avg pairwise ρ
CO2	6	15	32	-1.117	0.264	122.039	0	-0.051
WS	6	15	30.7	6.112	9.84E-10	286.08	0	0.285
AE	6	10	30	4.44	8.98E-06	100.032	1.29E-14	0.314
EN	6	15	32	19.581	0	386.945	0	0.894
GDP	6	15	32	-2.472	0.0134	79.198	9.79E-11	-0.113
AGR	6	15	24.6	7.68	1.60E-14	103.915	2.33E-15	0.4

The results indicate strong cross-sectional dependence for most series in the GCC panel. Water stress (WS), agricultural efficiency (AE), energy use (EN), GDP per capita (GDP), and agricultural value added (AGR) all reject the null of cross-sectional independence

at conventional levels under both Pesaran CD and BP-LM tests. For CO_2 emissions, the Pesaran CD test is not significant, but the BP-LM test strongly rejects independence, suggesting that dependence may exist but with mixed positive and negative pairwise correlations that reduce the average correlation detected by the CD statistic. Overall, the evidence supports the use of second-generation panel methods that account for cross-sectional dependence and heterogeneous dynamics.

3.4. Unit root tests

To avoid spurious regression results, the stationarity of the variables is examined using panel unit root tests that allow for heterogeneity and common shocks.

Table 5
Second-generation panel unit root tests (CIPS)

Variable	CIPS statistic	Countries used
CO2	-0.991	6
WS	-2.033	6
AE	-3.399	5
EN	-1.608	6
GDP	-1.52	6
AGR	-1.697	6

Panel unit root tests are conducted using the cross-sectionally augmented IPS (CIPS) test proposed by Pesaran (2007). The results indicate that most variables are non-stationary in levels, while agricultural efficiency (AE) is stationary at the 5% level. These findings suggest a mixture of I(0) and I(1) processes, justifying the use of Westerlund (2007) panel cointegration tests, which remain valid under such conditions.

4. Results

This section reports the empirical findings of the study, including panel cointegration results, long-run CCE-MG estimates, and short-run and long-run causality evidence from the ECM framework. Robustness checks based on alternative lag structures and Dumitrescu–Hurlin panel Granger causality tests are also presented.

4.1. Westerlund (2007) panel cointegration tests

The existence of a long-run relationship among CO_2 emissions, water stress, agricultural efficiency, energy use, economic activity, and agricultural value added is examined using the error-correction-based panel cointegration tests proposed by Westerlund (2007). The results are reported in Table 6.

Table 6
Westerlund (2007) panel cointegration tests

Statistic	Value	p-value
Gt	-4.144	3.41E-05
Pt	-10.151	0

As reported in Table 6, the group-mean statistic (Gt = − 4.144, $p < 0.01$) strongly rejects the null hypothesis of no cointegration, indicating the presence of a long-run relationship for at least part of the panel. In addition, the panel statistic (Pt = − 10.151, p = 0.000) also rejects the null hypothesis at the 1% significance level, providing robust evidence of a stable long-run equilibrium relationship among the variables across GCC countries.

Having established the existence of a long-run cointegrating relationship among the variables, the next step is to estimate the long-run elasticities.

4.2. Long-run estimation

The long-run estimation results based on the CCE-MG estimator are summarized in Table 7.

Table 7
CCE-MG long-run elasticities (Dependent variable: ln(CO2))

Variable	CCE-MG coef	Std. Error	t-stat	p-value
WS	-0.3787	0.1321	-2.867	0.0351
AE	-0.3238	0.3958	-0.818	0.451
EN	0.4234	0.089	4.758	0.00507
GDP	1.0172	0.2004	5.075	0.00385
AGR	-0.0847	0.026	-3.254	0.0226

The CCE-MG long-run estimates indicate that the main explanatory variables exert heterogeneous effects on CO_2 emissions across GCC countries. Water stress (WS) has a negative and statistically significant long-run effect on emissions (coefficient = − 0.3787, t = − 2.867, p = 0.0351), suggesting that persistent pressure on freshwater resources is associated with long-run structural adjustments that reduce CO_2 emissions. This finding provides support for Hypothesis H1, confirming that water stress significantly affects environmental pressure in the long run.

By contrast, agricultural efficiency (AE) exhibits a negative but statistically insignificant coefficient (− 0.3238, t = − 0.818, p = 0.451), indicating that improvements in water productivity do not translate into measurable reductions in aggregate CO_2 emissions at the macroeconomic level. This result implies that efficiency gains may be offset by scale or rebound effects, or that the relatively small size of the agricultural sector limits its impact on overall emissions. Consequently, Hypothesis H2 is not supported by the long-run estimates.

Energy use (EN) emerges as a key driver of CO_2 emissions, with a positive and highly significant coefficient (0.4234, t = 4.758, p = 0.00507). This result highlights the dominant role of energy consumption in shaping long-run environmental outcomes in GCC economies and is consistent with their fossil-fuel-based energy systems. The strong and robust effect of energy use provides clear support for Hypothesis H3.

Turning to the control variables, GDP per capita shows a positive and statistically significant association with CO_2 emissions (1.0172, t = 5.075, p = 0.00385), reflecting scale effects linked to economic activity in energy-intensive economies. In contrast, agriculture value added (AGR) is negatively and significantly related to emissions (− 0.0847, t = − 3.254, p = 0.0226), suggesting that differences in sectoral structure and agricultural intensity are associated with lower long-run environmental pressure. These results confirm that the control variables behave in line with theoretical expectations and help isolate the net effects of the main explanatory variables.

Overall, the long-run CCE-MG results underscore the central role of energy use in driving CO_2 emissions, reveal a significant long-run adjustment effect associated with water stress, and indicate that agricultural efficiency does not exert a robust mitigating effect at the aggregate level.

To distinguish between short-run dynamics and long-run equilibrium adjustment underlying these relationships, the next section examines causality using an error-correction–based framework

4.3. Dynamic panel causality results

This paragraph examines both short-run and long-run causal relationships among the variables using a panel error-correction model (ECM), complemented by country-level ECM estimates to capture heterogeneity across GCC countries.

-Panel ECM Causality

The panel ECM causality results are presented in Table 8.

Table 8
Panel error-correction causality tests (Dependent: Δln(CO2))

Test	Fisher χ^2	Panel p-value	Countries
ECT(-1) (long-run adjustment)	32.957	0.000277	5
Δln_WS(-1) (short-run causality)	12.983	0.225	5
Δln_AE(-1) (short-run causality)	7.327	0.694	5
Δln_EN(-1) (short-run causality)	26.777	0.00282	5
Δln_GDP(-1) (short-run causality)	6.752	0.749	5
Δln_AGR(-1) (short-run causality)	6.885	0.736	5

The panel ECM results provide clear evidence of long-run adjustment toward equilibrium, as indicated by the negative and highly significant error-correction term (ECT_{-1}: $\chi^2 = 32.957$, $p = 0.000277$), confirming the existence of long-run causality running from the explanatory variables to CO_2 emissions in GCC countries. In the short run, energy use (EN) is the only explanatory variable that exerts a statistically significant causal effect on emissions ($\chi^2 = 26.777$, $p = 0.00282$), reinforcing its dominant role in driving short-term emission dynamics and providing support for Hypothesis H3 in the short run.

By contrast, water stress (WS) ($p = 0.225$) and agricultural efficiency (AE) ($p = 0.694$) do not exhibit significant short-run causal effects, indicating that their influence on CO_2 emissions materializes primarily through long-run structural adjustment rather than immediate responses. These findings imply long-run support for Hypothesis H1, while Hypothesis H2 is not supported in the short run. The control variables, GDP per capita ($p = 0.749$) and agriculture value added ($p = 0.736$), are also insignificant in the short run, suggesting that scale and sectoral structure effects operate mainly over longer horizons.

Overall, the ECM results highlight a clear distinction between energy-driven short-run emission dynamics and resource-related long-run adjustment mechanisms. To further assess the causal patterns and account for cross-country heterogeneity, the next section presents country-level ECM estimates.

-Country ECM

To capture cross-country heterogeneity in short-run dynamics and long-run adjustment, country-level error-correction models are estimated, and the results are reported in Table 9.

Table 9
Country-level ECM results

Country	Obs (ECM)	ECT(-1) coef	ECT(-1) t	ECT(-1) p	Δln_WS(-1) p	Δln_AE(-1) p	Δln_EN(-1) p	Δln_GDP(-1) p	Δln_AGR(-1) p
ARE	28.0000	-0.4602	-2.0889	0.0491	0.516	0.304	0.952	0.611	0.759
KWT	25.0000	-0.7692	-3.3265	0.0038	0.487	0.894	0.00129	0.769	0.265
OMN	28.0000	0.0233	0.1465	0.8849	0.201	0.208	0.257	0.499	0.582
QAT	20.0000	-1.8128	-3.6893	0.0027	0.158	0.944	0.0207	0.225	0.362
SAU	28.0000	-0.3796	-1.4680	0.1569	0.189	0.48	0.235	0.647	0.757

The country-level ECM results reported in Table 9 reveal marked heterogeneity across GCC countries. The error-correction term is negative and statistically significant for the United Arab Emirates (− 0.4602, $p = 0.0491$), Kuwait (− 0.7692, $p = 0.0038$), and Qatar (− 1.8128, $p = 0.0027$), indicating effective long-run adjustment toward equilibrium in these economies. By contrast, the ECT is insignificant for Oman ($p = 0.8849$) and Saudi Arabia ($p = 0.1569$), suggesting weaker adjustment dynamics. In the short run,

energy use is the only variable that Granger-causes CO_2 emissions, and only in Kuwait (p = 0.00129) and Qatar (p = 0.0207), while water stress, agricultural efficiency, GDP per capita, and agricultural value added show no significant short-run effects. Overall, these findings confirm that long-run adjustment and short-run emission dynamics are highly country-specific within the GCC.

To assess the robustness of the main findings, additional causality analysis is conducted using an alternative panel approach.

5. Robustness checks

Robustness is assessed using ECM causality tests with two lags and Dumitrescu–Hurlin panel Granger causality analysis.

Robustness ECM causality tests with two lags

Table 10 reports the results of the robustness ECM causality tests estimated with two lags, where short-run causality toward CO_2 emissions is jointly assessed through the lagged first-difference terms

Table 10
Robustness ECM causality tests with two lags (Dependent: ΔlnCO2))

Test	Fisher χ^2	Panel p-value	Countries
ECT(-1) (long-run adjustment)	33.068	5.99E-05	4
Δln_WS(-1,-2) (short-run causality)	5.419	0.712	4
Δln_AE(-1,-2) (short-run causality)	14.6	0.0674	4
Δln_EN(-1,-2) (short-run causality)	93.955	1.11E-16	4
Δln_GDP(-1,-2) (short-run causality)	43.095	8.43E-07	4
Δln_AGR(-1,-2) (short-run causality)	5.252	0.73	4

Table 10 reports the robustness ECM causality results based on a two-lag specification and confirms the stability of the baseline findings. The error-correction term remains negative and highly significant (Fisher $\chi^2 = 33.068$, $p = 5.99\times10^{-5}$), providing strong evidence of robust long-run adjustment toward equilibrium. In the short run, energy use (EN) continues to exert a strong and statistically significant causal effect on CO_2 emissions ($\chi^2 = 93.955$, $p < 0.001$), reinforcing its dominant role in short-term emission dynamics and offering robust support for Hypothesis H3.

By contrast, water stress (WS) remains statistically insignificant in the short run, indicating that its influence on emissions operates primarily through long-run structural mechanisms, consistent with long-run support for Hypothesis H1. Agricultural efficiency (AE) displays only marginal short-run significance (p = 0.067), which is insufficient to provide robust support for Hypothesis H2 and suggests that efficiency gains do not translate into immediate emission reductions.

Among the control variables, GDP per capita shows a significant short-run causal effect on CO_2 emissions ($\chi^2 = 43.095$, $p < 0.001$), reflecting scale effects under alternative lag specifications, while agriculture value added remains insignificant. The robustness analysis is conducted on a reduced panel of four countries due to the longer lag structure, which requires sufficiently long and continuous time series.

Overall, the robustness results reaffirm that short-run emission dynamics in GCC countries are primarily energy-driven, whereas water stress and agricultural efficiency influence emissions mainly through longer-term adjustment processes.

Dumitrescu–Hurlin panel Granger causality

Table 11 reports the results of the Dumitrescu–Hurlin panel Granger causality tests, which provide complementary evidence on short-run causal relationships among the variables.

Table 11
Dumitrescu–Hurlin panel Granger causality tests (lags = 1, 1992–2023)

Dependent	Cause	Lags	Countries	Wbar	Zbar	p-value
ln(CO2)	ln(WS)	1	6	2.027	1.778	0.0754
ln(CO2)	ln(1 + AE)	1	5	1.126	0.199	0.842
ln(CO2)	ln(EN)	1	6	2.217	2.108	0.035
ln(CO2)	ln(GDP)	1	6	1.381	0.66	0.51
ln(CO2)	ln(AGR)	1	6	1.592	1.025	0.305
ln(WS)	ln(CO2)	1	6	4.572	6.187	6.15E-10
ln(1 + AE)	ln(CO2)	1	5	3.341	3.702	0.000214
ln(EN)	ln(CO2)	1	6	6.245	9.085	0
ln(GDP)	ln(CO2)	1	6	1.452	0.783	0.434
ln(AGR)	ln(CO2)	1	6	1.264	0.457	0.648

The Dumitrescu–Hurlin panel Granger causality results in Table 11 provide further insight into the short-run dynamics among the main explanatory variables and CO_2 emissions. Energy use (EN) is the only explanatory variable that robustly Granger-causes CO_2 emissions in the short run ($\bar{Z}$ = 2.108, p = 0.035), confirming its dominant role in short-term emission dynamics and providing additional support for Hypothesis H3. Water stress (WS) exhibits only marginal predictive power at the 10% significance level (p = 0.0754), suggesting weak short-run influence and reinforcing the view that its impact on emissions operates mainly through long-run structural channels, consistent with partial long-run support for Hypothesis H1. By contrast, agricultural efficiency (AE) does not display significant short-run causality toward emissions, indicating that Hypothesis H2 is not supported in the short run.

In the reverse direction, the results reveal strong feedback effects from CO_2 emissions to the core explanatory variables. CO_2 emissions Granger-cause water stress ($\bar{Z}$ = 6.187, p < 0.001), agricultural efficiency ($\bar{Z}$ = 3.702, p = 0.000214), and energy use ($\bar{Z}$ = 9.085, p = 0.000), highlighting endogenous interactions within the water–energy–environment nexus. No significant reverse causality is detected for the control variables, GDP per capita and agriculture value added. Overall, these findings reinforce the central short-run role of energy use, while underscoring the presence of bidirectional feedback mechanisms linking emissions to resource stress and efficiency dynamics.

The results allow for an explicit evaluation of the hypotheses proposed in this study.

Table 12 summarizes the empirical assessment of Hypotheses H1–H3, indicating which hypotheses are supported, partially supported, or not supported by the results.

Table 11
Summary of hypothesis testing results

Hypothesis	Expected effect on CO_2	Long-run result	Short-run result	Conclusion
H1: Water stress → CO_2	Negative	Significant	Not significant	Partially supported (long run only)
H2: Agricultural efficiency → CO_2	Negative	Not significant	Not significant	Not supported
H3: Energy use → CO_2	Positive	Significant	Significant	Supported

6. Discussion

This study contributes to the water-energy-agriculture-environment nexus literature by providing robust evidence from GCC countries, a region characterized by acute water scarcity and energy-intensive development pathways. The results confirm a

stable long-run relationship linking water stress, agricultural efficiency, energy use, and CO_2 emissions, while revealing clear asymmetries between long-run structural effects and short-run dynamics. Environmental pressure in the GCC thus reflects both immediate energy-driven mechanisms and slower resource-related adjustment processes.

The long-run estimates highlight the dominant role of energy use in driving CO_2 emissions, consistent with energy-emissions nexus theory and prior evidence for fossil fuel-dependent economies (Sadorsky, 2012; Omri, 2014; Al-Mulali & Ozturk, 2016). Economic activity in the GCC remains closely coupled with energy consumption, indicating limited decoupling between growth and emissions despite recent diversification efforts. This pattern aligns with Legg (2021), which emphasizes that scale effects dominate environmental outcomes in the absence of deep energy system transformation. Energy-intensive production structures, climate-driven cooling demand, and carbon-intensive water supply technologies further reinforce this linkage.

Agricultural efficiency, proxied by water productivity, does not exhibit a statistically significant long-run effect on CO_2 emissions. This suggests that efficiency gains within agriculture have not translated into measurable reductions in aggregate emissions, likely due to rebound and scale effects documented in the literature (Mekonnen & Hoekstra, 2011; Thenkabail, 2008; Chandio et al., 2020). Given agriculture's relatively small contribution to GCC GDP, efficiency improvements may primarily affect localized water outcomes rather than economy-wide environmental pressure.

The significant long-run association between water stress and CO_2 emissions underscores the indirect environmental consequences of freshwater scarcity. Persistent water stress appears to increase reliance on energy-intensive adaptation strategies, such as groundwater pumping and desalination, which are widespread across the GCC (Wada et al., 2017; FAO, 2017). This finding supports recent nexus-based frameworks emphasizing that water security and climate mitigation are deeply interconnected in arid economies reliant on carbon-intensive infrastructure (Legg, 2021; Wada et al., 2017). The absence of robust short-run effects suggests that the impact of water stress materializes gradually through long-run structural and technological adjustment.

The ECM causality results further clarify the temporal structure of these relationships. The negative and statistically significant error-correction term confirms long-run causality running from resource use toward CO_2 emissions, with deviations from equilibrium corrected over time. This mechanism remains robust under alternative lag specifications. In the short run, energy use consistently emerges as the primary driver of emission changes, reflecting the immediacy with which energy demand shocks translate into environmental pressure (Shahbaz et al., 2013; Omri, 2014, Apiah et al., 2018). Water stress and agricultural efficiency, by contrast, do not display robust short-run causal effects.

Country-level results reveal notable heterogeneity across GCC economies. Long-run adjustment is evident in the United Arab Emirates, Kuwait, and Qatar, while weaker dynamics in Bahrain and Oman may reflect differences in economic scale, sectoral structure, or institutional capacity. Such heterogeneity is consistent with the panel econometrics literature, which emphasizes the context-dependent nature of environmental dynamics even within relatively homogeneous regional blocs (Pesaran, 2007).

Robustness checks confirm the stability of the main findings. Alternative ECM specifications preserve the dominance of energy use in short-run emissions dynamics and confirm long-run adjustment toward equilibrium, while water stress and agricultural efficiency remain largely insignificant in the short run. Dumitrescu-Hurlin panel Granger causality tests further corroborate these results and reveal feedback effects from CO_2 emissions to water stress, agricultural efficiency, and energy use, highlighting the endogenous nature of the nexus.

Overall, the findings indicate that short-run emissions dynamics in GCC countries are primarily energy-driven, whereas water stress and agricultural efficiency influence emissions mainly through long-run structural mechanisms. Short-term mitigation therefore hinges on energy efficiency and decarbonization, while long-term sustainability requires integrated water–energy–agriculture policies that reduce the energy intensity of water and food systems. By distinguishing clearly between short-run dynamics and long-run adjustment, this study advances a more nuanced understanding of sustainability challenges in water-scarce, energy-dependent economies.

7. Policy implications

The findings of this study offer clear guidance for sustainability policy in GCC countries. The strong and consistent effect of energy use on CO_2 emissions in both the long run and the short run indicates that energy-sector reforms represent the most effective instrument for immediate emission reduction. Enhancing energy efficiency, expanding renewable energy deployment, and reducing reliance on fossil fuels, particularly in electricity generation, industry, cooling demand, and water-related infrastructure, are essential to weakening the growth-emissions link in the region.

The significant long-run association between water stress and CO_2 emissions highlights the importance of integrated water-energy policy frameworks. In water-scarce GCC economies, water security increasingly depends on energy-intensive technologies such as desalination and groundwater extraction. When powered by fossil fuels, these measures risk reinforcing long-term emissions growth. Policies should therefore prioritize renewable-powered desalination, energy-efficient pumping, and demand-side water management to align water security objectives with climate mitigation.

Although agricultural efficiency does not exert a robust short-run effect on emissions, it remains relevant for long-term sustainability. Policies promoting modern irrigation, precision agriculture, and water-saving technologies can reduce pressure on scarce freshwater resources and limit the energy intensity of agricultural production. However, the absence of a measurable aggregate emissions effect suggests that agricultural efficiency policies should primarily target water sustainability, with broader climate benefits depending on complementary energy-sector reforms.

Finally, the heterogeneity observed across GCC countries implies that policy design should be context-specific, reflecting differences in economic structure and institutional capacity. While regional coordination can support knowledge sharing and technology diffusion, national calibration remains crucial. Overall, the results indicate that short-term emission mitigation in the GCC hinges on energy-sector transformation, whereas long-term environmental sustainability requires coordinated water-energy-agriculture strategies that reduce the energy intensity of resource use.

8. Conclusion

This study analyzed the long-run and short-run relationships between water stress, agricultural efficiency, energy use, and CO_2 emissions in GCC countries over the period 1992–2023 using a second-generation panel econometric framework that accounts for cross-sectional dependence and heterogeneity. By combining cointegration analysis, Common Correlated Effects estimation, and error-correction–based causality tests, the study offers an integrated empirical assessment of environmental pressure in water-scarce, energy-dependent economies.

The main contribution of the study lies in its explicit incorporation of direct indicators of water stress and agricultural efficiency within a unified nexus-based framework applied to the GCC. Unlike much of the existing literature, which often relies on indirect proxies or broader regional samples, this analysis provides region-specific evidence from one of the most water-constrained areas globally and highlights the importance of distinguishing between short-run dynamics and long-run adjustment processes when evaluating environmental sustainability.

Several limitations should be acknowledged. First, the analysis relies on aggregate, country-level indicators, which may mask sectoral and within-country heterogeneity in resource use and emissions. Second, data availability restricts the sample size and precludes the inclusion of more granular measures of technological change, renewable energy adoption, or institutional quality. Third, while the econometric framework captures long-run equilibrium relationships and short-run dynamics, it does not explicitly model nonlinearities or potential threshold effects that may characterize resource–environment interactions in highly water-stressed economies.

Despite these limitations, the study provides a robust empirical foundation for future research. Subsequent work could extend the analysis by incorporating sector-level data, alternative measures of agricultural efficiency, or nonlinear modeling approaches to further explore the complexity of the water–energy–agriculture–environment nexus. Overall, this study contributes to a more precise empirical understanding of sustainability challenges in water-scarce economies and offers a basis for advancing both methodological and applied research in this field.

Declarations

Funding

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2604).

Author Contribution

The article is written by only one author

Acknowledgement

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2604).

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