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Exploring the Long-Term Relationship Between Freshwater Withdrawals and Agricultural Output in Azerbaijan: Evidence from ARDL and Cointegration Analysis (2000-2021)

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ABSTRACT

Effective management of water resources plays a critical role in maintaining agricultural productivity, especially in regions that face increasing water scarcity. In the case of Azerbaijan, where agriculture constitutes a significant component of the national economy and freshwater resources are under growing pressure, it is essential to understand the relationship between water consumption and agricultural output for informed policy development. This study explores the long-term equilibrium association between annual freshwater withdrawals and agricultural gross domestic product for the period from 2000 to 2021, based on annual time series data. The autoregressive distributed lag bounds testing approach indicates the presence of a cointegrated relationship, as the computed F-statistic of 4.986 exceeds the upper bound critical values at both the five percent and ten percent significance levels. Subsequent analysis using the fully modified ordinary least squares method identifies a statistically significant and positive long-run relationship, showing that a one percent increase in agricultural output leads to a 0.025 percent rise in freshwater usage. The Engle-Granger cointegration test further validates this finding, yielding a tau-statistic p-value of 0.015, which confirms the existence of a stable long-term connection between the variables. These findings highlight the importance of implementing coherent water and agricultural policies in Azerbaijan, including measures to improve irrigation efficiency, invest in water-conserving technologies, and ensure that agricultural development is aligned with the principles of sustainable water resource management.

1. INTRODUCTION

The Sustainable Development Goals (SDGs) constitute a vital framework for advancing global sustainability, with particular emphasis on the responsible utilization of clean water resources. Within this framework, Goal 6 specifically targets the assurance of universal access to water and sanitation through sustainable management approaches [1]. Agricultural activities are responsible for approximately 70% of global freshwater withdrawals. In comparison, industrial usage accounts for nearly 20%, while domestic or municipal consumption represents about 12% of the total [2]. The escalating global population and changing dietary trends toward water-intensive crops have heightened demands on freshwater resources, making the sustainable management of agricultural production and water conservation a central priority in development, environmental policy, and food security initiatives.

Water resources have become a strategically significant issue in Azerbaijan, reflecting broader global challenges. With food security emerging as a key international priority and agricultural activities expanding within the country, the demand for clean water has grown increasingly urgent. This urgency has been exacerbated by the declining water levels observed in several rivers. Azerbaijan's surface water resources are estimated at approximately 30 billion cubic meters, of which only 30% are formed within national borders, while the remaining 70% are derived from neighboring countries. However, the effects of recent climate change have led to a substantial reduction in these resources, with the total volume decreasing to 17 billion cubic meters as of 2022 [3].

This issue remains relatively new within Azerbaijan's scientific landscape, resulting in a limited body of empirical research and long-term dynamic analysis. There is a pressing need to engage more academic researchers in exploring this area to support evidence-based policy development and close existing knowledge gaps.

The management of freshwater resources in Azerbaijan is of paramount importance from ecological, economic, and public safety perspectives. Azerbaijan possesses surface water reserves estimated at 27 km³, with potable water resources being both limited and spatially heterogeneous throughout the country. In periods of drought, these reserves diminish to approximately 20–21 km³. The principal contributors to surface water availability comprise rivers, lakes, reservoirs, and glacial sources [4]. Recent assessments estimate that Azerbaijan's renewable freshwater resources amount to approximately 26 billion cubic meters, and the observed decline in these reserves has become a significant concern for the sustainability of water resources and long-term water security [5]. Since 2015, Azerbaijan has pursued agricultural modernization to reduce food imports and increase exports, addressing issues such as land fragmentation, inefficient irrigation, and limited farmer expertise. Sustainable development in the sector can be achieved through integrated measures, including land consolidation, modern irrigation systems, institutional capacity-building, and enhanced agricultural education, providing practical insights for national strategies and comparable emerging economies [6].

This study investigates the long-term relationships between freshwater withdrawals and total agricultural output levels in Azerbaijan using advanced econometric methods. It aims to determine whether these variables exhibit a stable equilibrium over time within the Azerbaijani context and to assess the degree to which changes in water withdrawals affect or are affected by variations in agricultural productivity. The outcomes are intended to deliver empirical insights that inform the development of sustainable water management policies, climate-resilient agricultural practices, and the promotion of food security and environmental sustainability in Azerbaijan.

2. LITERATURE REVIEW

The interconnection between freshwater withdrawals and agricultural productivity has garnered extensive attention in the fields of environmental economics, water resource management, and agricultural studies. The critical importance of understanding how water use directly impacts agricultural output and crop production, particularly in regions where water scarcity poses a significant threat to food security and sustainable development.

Several international studies have empirically analyzed the long-term dynamics between freshwater use and agricultural productivity. For instance, Egbo et al. [7] investigated water use efficiency within BRICS countries, revealing sectoral disparities where agricultural sectors often demonstrate higher water use efficiency relative to industrial sectors. Their findings emphasize the significance of efficient water management policies and investment in water infrastructure to enhance agricultural productivity. Similarly, Liu et al. [8] employed integrated global modeling to highlight trade-offs involved in reducing unsustainable irrigation practices. Their work illustrated that while water conservation measures can mitigate resource depletion, they may also lead to unintended consequences such as decreased crop yields and increased food insecurity if not carefully managed within broader socio-environmental contexts.

Regionally, studies focusing on semi-arid and arid countries demonstrate the complexity of managing freshwater resources for agriculture. Eslamifar et al. [9] utilized system dynamics modeling to evaluate the effects of fallowing on water consumption and agricultural income in semi-arid valleys, showing that strategic land fallowing can substantially reduce water withdrawals with only modest economic trade-offs. This insight is especially relevant to Azerbaijan, where agriculture represents a vital sector but faces challenges from limited and unevenly distributed water resources.

The arid climate and shared water resources of Central Asia are increasingly challenged by climate change, demographic expansion, and pollution, underscoring the need for comprehensive management strategies that incorporate environmental constraints, socio-cultural factors, and geopolitical considerations to ensure sustainable water resource governance [10].

Environmental and resource-related issues manifest differently across regions and sectors, influencing both food security and the quality of urban living. Amin et al. [11] provide evidence that land use, green energy, and water resources significantly shape food accessibility in emerging economies, whereas Szemerédi and Remsei [12] show that exposure to urban heat islands in Győr, Hungary, is unequally distributed among population groups, depending on residential and demographic factors. Together, these studies highlight the importance of implementing environmental policies that are both spatially and socially responsive.

In the Azerbaijani context, empirical research examining the nexus between freshwater use and agricultural productivity remains comparatively limited, despite the sector's significant role in national food security and rural livelihoods. Gulaliyev et al. [13] conducted a comprehensive assessment of agricultural sustainability in Azerbaijan, noting that while social dimensions scored moderately, both economic and environmental sustainability—closely linked to resource use—remained weak. The study highlighted the need for integrated strategies addressing water resource management to bridge the welfare gap between urban industrial zones and rural agricultural areas. Complementary investigations have underscored the importance of water infrastructure investment and efficient irrigation practices to bolster agricultural output under changing climatic and socio-economic conditions [14].

Utilizing comprehensive geospatial data and a dynamic spatial equilibrium model, the study examines how distortions in agricultural and trade policies influence global water scarcity and welfare. The findings indicate that although water-intensive crops are generally concentrated in water-rich areas, trade barriers and policy shifts can intensify groundwater depletion and produce varied effects across different regions [15]. More broadly, theoretical and empirical frameworks emphasize that the relationship between freshwater withdrawals and agricultural output is influenced by a range of mediating factors, including technological innovation, land use patterns, economic growth, and policy environments [16]. These studies collectively point to the necessity of adopting holistic and regionally tailored water management approaches that balance productivity goals with sustainability imperatives. Similar results have been reported in several studies exploring this topic from different perspectives. These studies consistently highlight both the benefits of improved water management for agriculture and the environmental trade-offs involved, emphasizing the need for balanced and context-specific approaches [17-19].

Despite these advances, there remains a notable gap in long-term, country-specific empirical research focused on Azerbaijan's agricultural water use dynamics. Most existing studies either adopt broad regional perspectives or focus on short-term analyses, limiting their capacity to inform sustainable water and agricultural policies that are sensitive to local hydrological and socio-economic conditions. Therefore, the present research seeks to address this gap by providing an empirical investigation into the long-term relationship between freshwater withdrawals, agricultural output, and crop production in Azerbaijan, thereby contributing valuable insights to inform sustainable agricultural water management in the country.

3. DATA AND METHODOLOGY

This research explores the long-run relationship between freshwater withdrawals and agricultural performance in Azerbaijan using annual time series data. The analysis focuses on the following key variables:

- Annual Freshwater Withdrawals (AFW) – expressed as a percentage of total renewable freshwater resources, this variable highlights the extent of water utilization across sectors, with an emphasis on agricultural use.
- Agricultural GDP (AGDP) – measured in Azerbaijani manat, this variable represents the economic output of the agricultural sector.

The dataset encompasses the most recent period for which complete data are available, obtained from the World Bank [20, 21] and the State Statistical Committee of the Republic of Azerbaijan [22]. All variables have been log-transformed to address heteroskedasticity and to facilitate the interpretation of coefficients in terms of elasticities.

Figure 1 presents two bar charts depicting key trends in Azerbaijan's agricultural sector between 2000 and 2021. The first chart reveals that agriculture has consistently accounted for a substantial share of total annual freshwater withdrawals, ranging between approximately 86% and 93%. This underscores the sector's dominant role in the country's overall water consumption. he second graph shows a steady and substantial increase in Agricultural GDP, measured in Azerbaijani manat, indicating continuous economic growth within the sector.

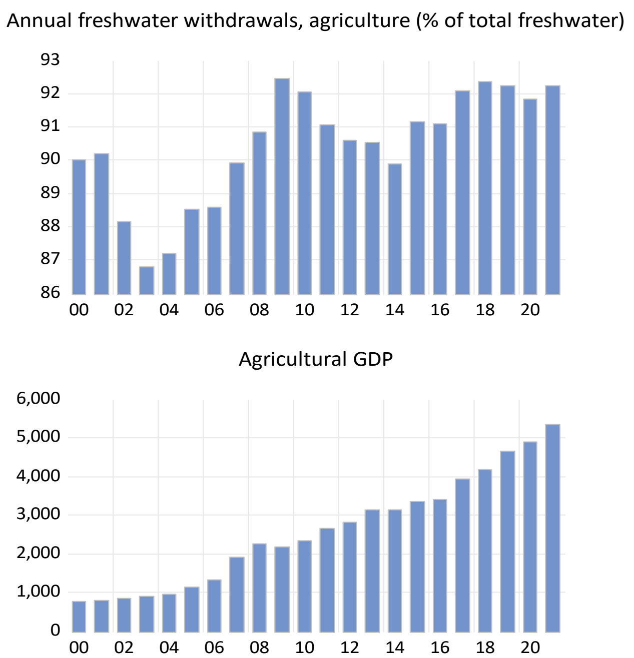

Figure 1. Key trends in Azerbaijan's agricultural sector: Freshwater withdrawals and agricultural GDP (2000-2021)

Table 1 displays the descriptive statistics for AFW and AGDP. Importantly, the Jarque-Bera probability values for all variables exceed the 0.05 threshold, indicating that the null hypothesis of normality cannot be rejected. This suggests that the data series are approximately normally distributed, a condition favorable for the application of various parametric statistical techniques.

Table 1. Descriptive statistics of the variables

Statistic	AFW	AGDP
Mean	90.44684	2583.318
Median	90.71918	2494.050
Maximum	92.46858	5336.800
Minimum	86.79407	758.9000
Std Dev.	1.691779	1433.236
Skewness	-0.704499	0.301268
Kurtosis	2.511876	1.993957
Jarque-Bera	2.038243	1.260576
Probability	0.360912	0.532438

Figure 2 illustrates the logarithmic trends of annual freshwater withdrawals (L_AFW) and agricultural GDP (L_AGDP) in Azerbaijan over the observed period. The trajectory of L_AGDP exhibits a consistent upward movement, indicating continuous growth in agricultural output. In contrast, L_AFW shows minimal variation over time, suggesting that advancements in agricultural performance have occurred without a proportional increase in freshwater extraction.

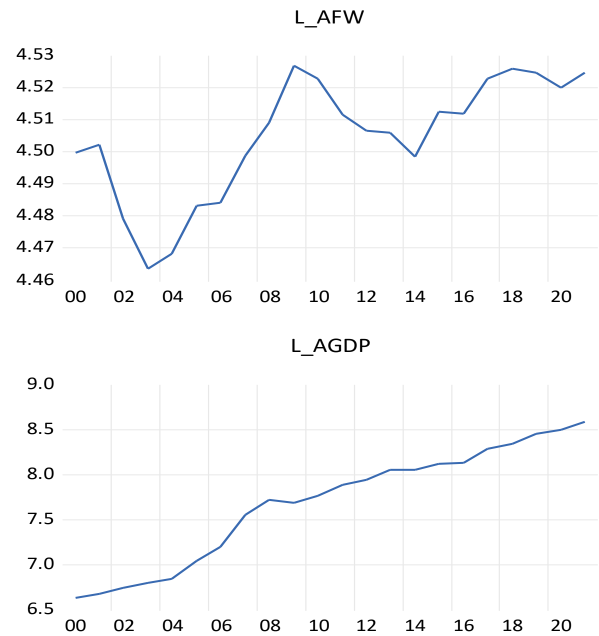

Figure 2. Logarithmic trends of the variables in Azerbaijan (2000-2021)

Cointegration testing holds a prominent position in contemporary econometric research, and the application of such models for cointegration analysis represents a significant and evolving area of scientific inquiry [23].

The methodological framework employs a structured econometric approach to assess the dynamic and long-term relationships among the selected variables. Initially, Unit Root tests were conducted to determine the stationarity properties, confirming that all variables are integrated of order I(0) or I(1), justifying the use of the ARDL model. The ARDL bounds testing approach, based on Pesaran et al. [24], was applied to estimate both short- and long-run dynamics, with lag lengths selected using the Akaike Information Criterion (AIC). The Fully Modified Ordinary Least Squares (FMOLS) approach is regarded as an appropriate method for quantitatively assessing long-run relationships between variables and evaluating the extent of their interactions [25-27]. To reinforce cointegration findings, the Engle and Granger [28] two-step method was used, confirming stationarity in the residuals from the long-run equation. Finally, the Error Correction Model (ECM) and diagnostic tests, including the Breusch-Pagan-Godfrey test and CUSUM-based stability checks, validated the robustness, stability, and reliability of the model.

4. RESULTS AND DISCUSSION

The stationarity characteristics of the variables were evaluated through the Augmented Dickey and Fuller [29] and Phillips and Perron [30] unit root tests. Findings from both approaches demonstrated that AGDP and AFW exhibit non-stationarity at their level forms but attain stationarity upon first differencing, confirming their integration of order one, I(1). The properties shown in Table 2 satisfy the conditions for applying the ARDL model, which permits the inclusion of variables integrated of order zero, I(0), or order one, I(1), provided that none are integrated of order two, I(2). Furthermore, the Engle-Granger cointegration method is applicable since it necessitates that all variables be I(1). Consequently, these results justify the use of both the ARDL bounds testing approach, the FMOLS test, and the Engle-Granger cointegration framework to explore potential long-run associations.

Table 2. Unit root test

Variable	Level		First Difference	
	ADF Test Statistic	PP Test Statistic	ADF Test Statistic	PP Test Statistic
L_AFW	-1.039 (0.719)	-1.242 (0.635)	-3.250 (0.031)*	-3.250 (0.031)*
L_AGDP	-0.915 (0.762)	-0.890 (0.770)	-3.457 (0.020)*	-3.457 (0.020)*

*Significant at 5% level.

In Table 3, the ARDL bounds testing approach was utilized to assess the long-run relationship between annual freshwater withdrawals for agriculture (AFW) and agricultural GDP (AGDP) in Azerbaijan over the period 2000 to 2021. The computed F-statistic (4.986) significantly exceeds the upper bound critical values at the 5% and 10% significance levels. This provides the evidence to reject the null hypothesis of no long-run relationship, confirming the existence of a statistically significant cointegration among the variables.

Table 3. F-bounds test

Test Statistic	Value	Signif.	1(0)	1(1)
F-statistic	4.986	10%	3.02	3.51
k	1	5%	3.62	4.16

As presented in Table 4, the ECM Regression test result validates the existence of a stable long-run relationship between Agricultural GDP and freshwater withdrawals in Azerbaijan, confirming that deviations from equilibrium are gradually corrected over time. The diagnostic test outcomes indicate that the ARDL model is both statistically adequate and correctly specified. The absence of serial correlation, heteroskedasticity, and non-normality in the residuals is confirmed by p-values exceeding the conventional 0.05 significance level, thereby satisfying key classical linear regression assumptions.

Table 4. Diagnostic tests for the ARDL model

ECM Regression				
Variable	Coefficient	Std. Error	t-Statistic	P-value
CointEq(-1)	-0.971	0.227	-4.275	0.002
Breusch-Godfrey Serial Correlation LM Test				
F-statistic		1.484	Prob. F (2,7)	0.290
Obs*R-squared		5.360	Prob. Chi-Square (6)	0.068
Breusch-Pagan-Godfrey Heteroskedasticity Test				
F-statistic		0.988	Prob. F (8,9)	0.501
Obs*R-squared		8.416	Prob. Chi-Square (8)	0.393
Scaled Explained SS		0.395	Prob. Chi-Square (8)	0.996

In Figure 3, the CUSUM plot (top) indicates a structural break, evidenced by the blue line crossing below the lower 5% significance boundary, which signals parameter instability within the model. In contrast, the CUSUM of Squares plot (bottom) remains confined within its critical bounds, suggesting that the variance of the model's errors has remained stable throughout the sample period.

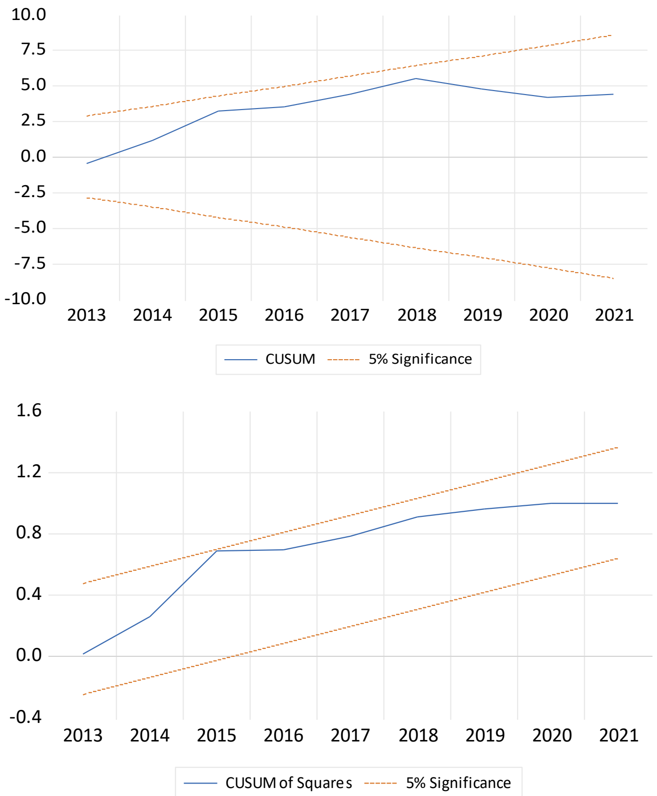

Figure 3. CUSUM test for parameter stability

As shown in Table 5, the FMOLS estimation identifies a statistically significant and positive long-run association between Agricultural GDP and freshwater withdrawals in Azerbaijan, indicating that a 1% increase in agricultural output results in a 0.025% rise in freshwater consumption. The model exhibits substantial explanatory capacity, accounting for approximately 67.5% of the variation in freshwater withdrawals through changes in agricultural GDP. These results highlight the sector's reliance on freshwater resources and emphasize the critical need for sustainable water management practices to support agricultural development.

Table 5. Fully modified OLS (FMOLS) test result

Variable	Coefficient	Std. Error	t-Statistic	Prob.
L_AGDP	0.025	0.005	4.840	0.000
C (Constant)	4.311	0.040	107.095	0.000
Statistic			Value	
R-squared			0.675	
Adjusted R-squared			0.658	

Table 6 presents the results of the Engle-Granger cointegration test, which assesses the presence of a long-run equilibrium relationship between the analyzed time series. The null hypothesis posits that the series are not cointegrated. The test results show that the tau-statistic has a p-value of 0.015, which is below the conventional significance threshold of 0.05. This leads to rejection of the null hypothesis, indicating evidence of cointegration. Although the z-statistic's p-value is comparatively high, the significant tau-statistic suggests a statistically meaningful long-run cointegrating relationship between the variables, provided that the sample size is adequate.

In Figure 4, the Jarque-Bera test results and residual diagnostics indicate that the residuals follow a normal distribution and exhibit desirable statistical properties. This finding reinforces the model's reliability concerning residual normality, a critical assumption for ensuring valid inference in numerous econometric analyses.

Based on key econometric findings, the estimated error correction term of -0.971 suggests a swift speed of adjustment, with approximately 97% of deviations from the long-run equilibrium between agricultural GDP and freshwater withdrawals being corrected within a single year. This reflects the system's capacity to respond efficiently to short-term disturbances, emphasizing the distinction between short-run fluctuations and the long-term positive elasticity identified through FMOLS estimation. The CUSUM test indicates a structural break during the sample period, potentially linked to significant events such as changes in irrigation policies, subsidy programs, or climatic shocks like droughts. While the CUSUM of squares test confirms the stability of error variance, the observed parameter instability points to the relevance of accounting for external influences when interpreting the model. The ARDL bounds testing approach provides robust evidence of a long-run relationship between the variables, and the diagnostic tests support the model's statistical adequacy and proper specification. These results carry important policy implications, highlighting the necessity of effective water resource management to support both immediate agricultural performance and sustained sectoral growth. The findings are consistent with those reported in related empirical studies using similar methodologies across different regions, though variations in elasticity estimates may stem from differences in environmental conditions, technological adoption, and agricultural practices. Overall, the evidence underscores the importance of context-specific water governance strategies informed by both domestic realities and international best practices to ensure the long-term sustainability of agricultural development in Azerbaijan.

Table 6. Engle-Granger cointegration test results

Test Type	Statistic	Value	Prob.*	Variables Examined	Deterministic	Lag Specification
Engle-Granger	Engle-Granger tau-statistic	-4.363	0.015	L_AFW, L_AGDP	C	lag=4 (Schwarz info criterion, maxlag=4)
	Engle-Granger z-statistic	20.739	1.000			

*Note: MacKinnon [31] p-values.

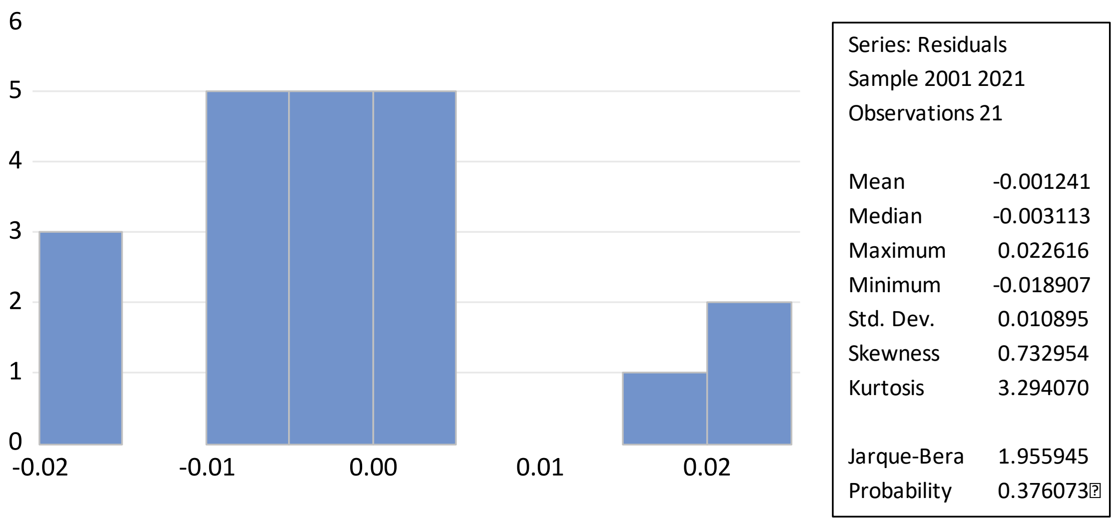

Figure 4. Residual normality test results

Empirical analysis confirms that annual freshwater withdrawals are cointegrated with agricultural GDP in Azerbaijan, indicating a stable long-run equilibrium relationship. This positive and sustained association between freshwater usage and agricultural performance highlights the critical importance of implementing sustainable water management strategies within the agricultural sector. Hossain et al. [32] and Saidmamatov et al. [33] applied the ARDL and Engle-Granger cointegration techniques to investigate related scientific issues across various regional contexts and arrived at consistent and comparable conclusions. Their findings reinforce the methodological robustness and applicability of these approaches in exploring long-run equilibrium relationships in diverse empirical settings. Given that expansions in agricultural GDP and crop production drive increased water demand over time, it is imperative for policymakers to prioritize investments in water-efficient irrigation technologies, promote crop varieties adapted to arid conditions, and adopt integrated water resource management approaches to ensure balanced and sustainable agricultural growth.

5.CONCLUSION

The empirical analysis presents strong and consistent evidence of a long-run equilibrium relationship between freshwater withdrawals and key indicators of agricultural performance in Azerbaijan. The ARDL bounds testing approach yielded a statistically significant F-statistic, indicating the presence of cointegration, while the FMOLS estimation confirmed a positive and statistically significant long-term association between agricultural GDP and freshwater usage. The model exhibits substantial explanatory power, capturing approximately 67.5% of the variation in freshwater withdrawals in response to changes in agricultural output. Furthermore, the Engle-Granger cointegration test produced statistically significant z-values, reinforcing the validity of a stable long-term relationship between the examined variables. Collectively, these findings highlight the intrinsic connection between agricultural development and escalating water demand, underscoring the urgent necessity for sustainable water resource management. Policy measures should focus on promoting the adoption of water-efficient irrigation techniques, encouraging the cultivation of drought-resilient crop varieties, and implementing comprehensive water governance frameworks. Such strategies are essential for reconciling the objectives of agricultural growth with the sustainable utilization of freshwater resources in Azerbaijan's agricultural sector. Nevertheless, it is crucial to acknowledge that the study relies on annual data, which may obscure intra-annual or seasonal variations in water consumption and agricultural dynamics. Future research should aim to incorporate higher-frequency data to capture temporal variability more effectively and consider integrating additional explanatory variables such as the impacts of climate change and the extent of groundwater overdraft. This would enable a more nuanced and comprehensive understanding of the multifaceted drivers influencing water demand and agricultural sustainability.

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