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Agricultural Productivity, Economic Performance, and Environmental Sustainability in Türkiye: Time-Series Evidence from 1992-2022

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Abstract. This study examines the relationships among agricultural productivity, input use, irrigation capacity, and sustainability in Türkiye from 1992 to 2022. Annual data from the World Bank were analyzed using descriptive statistics, correlation and multicollinearity tests, unit-root tests, the ARDL bounds-testing approach, robustness analyses, and Granger-causality tests. Separate Newey–West models were estimated for water stress, agricultural N_2O emissions, and agricultural value added per worker. The results indicate a stable long-run relationship in the cereal-productivity model. Fertilizer consumption and agricultural value added per worker are positively and significantly associated with cereal yield, with long-run elasticities of 0.254 and 0.324, respectively. Irrigated land, temperature, and precipitation are statistically insignificant. The error-correction coefficient indicates that approximately 93.5% of deviations from long-run equilibrium are corrected within one year. Granger-causality results indicate predictive precedence from cereal yield to fertilizer consumption, suggesting that reverse causality cannot be excluded. The sustainability models show that fertilizer consumption is positively associated with both agricultural N_2O emissions and agricultural value added per worker in the short run, while the water-stress model yields no significant results. Overall, the findings highlight a productivity–environment trade-off and support policies promoting fertilizer-use efficiency, precision nutrient management, and efficient irrigation.

Keywords: Agricultural productivity, cereal yield, fertilizer consumption, sustainable agriculture, Türkiye.

1 Introduction

Agriculture remains one of the most important sectors for food security, rural livelihoods, environmental sustainability, and economic development. Although the relative share of agriculture in national economies has declined in many countries due to industrialization and service-sector expansion, agricultural productivity continues to play a central role in ensuring food supply and supporting rural communities. Improving agricultural productivity is therefore not only an economic objective but also an essential component of food-system resilience and sustainable development.

In recent decades, agricultural systems have faced increasing pressure from population growth, climate change, land degradation, water scarcity, and rising input costs. These pressures have made the efficient use of agricultural resources more important than ever. Among the key determinants of agricultural productivity, fertilizer consumption and irrigation capacity occupy a particularly important position. Fertilizers can increase soil nutrient availability and contribute to higher crop yields, while irrigation can reduce dependence on rainfall

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and improve yield stability, particularly in areas affected by seasonal water variability. However, both fertilizer use and irrigation expansion also raise important sustainability concerns. Excessive or inefficient fertilizer use may contribute to soil degradation, nutrient losses, water pollution, and agricultural greenhouse-gas emissions, whereas inefficient irrigation may intensify pressure on limited freshwater resources. Agricultural productivity policies must therefore consider not only the quantity of output produced but also the environmental and resource costs associated with input use.

Türkiye provides an important case for examining the relationship between agricultural productivity and sustainability-related agricultural indicators. The country has diverse agroecological conditions, a significant agricultural land base, and an important role in regional food production. At the same time, Türkiye faces challenges related to water availability, climatic variability, agricultural input efficiency, and the need to improve productivity without increasing environmental pressure. These conditions make Türkiye a relevant setting for examining whether fertilizer use and irrigation capacity are associated with productivity gains and whether such gains are accompanied by environmental or economic sustainability outcomes.

Cereal yield is widely used as an indicator of agricultural productivity because cereals constitute a major component of food systems and agricultural production. Increases in cereal yield may reflect improvements in agricultural inputs, irrigation infrastructure, technology, and farm-management practices. However, productivity growth should not be evaluated only in terms of output expansion. From a sustainable-agriculture perspective, it is also necessary to consider how productivity is achieved and whether the production practices involved create environmental risks. In particular, fertilizer use may support cereal productivity while simultaneously increasing agricultural N_2O emissions, whereas irrigation expansion may have implications for water stress and resource availability. Agricultural value added per worker also provides an economic dimension by indicating whether changes in productivity and input use are associated with improvements in agricultural labor productivity.

Despite the importance of these relationships, macro-level evidence for Türkiye remains limited in several respects. Existing analyses often focus on individual agricultural inputs or estimate conventional regressions without fully addressing the time-series properties of the data. Such approaches may produce misleading results when variables contain unit roots, common trends, or long-run equilibrium relationships. Potential reverse causality is also relevant because higher agricultural productivity may encourage subsequent investment in fertilizer rather than fertilizer use operating only in the opposite direction. Moreover, sustainability is frequently discussed conceptually without being represented through direct environmental and economic indicators.

This study addresses these limitations by examining agricultural productivity and sustainability within an integrated time-series framework for Türkiye over the period 1992–2022. The main productivity model evaluates the long-run relationships of fertilizer consumption and irrigated land with cereal yield while controlling for annual mean temperature, annual total precipitation, and agricultural value added per worker. Separate sustainability models examine the short-run relationships of agricultural inputs with water stress, agricultural N_2O emissions, and agricultural value added per worker.

The empirical analysis applies Augmented Dickey–Fuller and Phillips–Perron unit-root tests, variance inflation factors, the autoregressive distributed lag bounds-testing approach, error-correction estimation, and post-estimation diagnostic and stability tests. The robustness analysis includes an alternative lag-selection criterion, one-year-lagged agricultural inputs, a deterministic time-trend specification, and exploratory sub-period estimations. A stable bivariate VAR model and Granger-causality Wald tests are also employed to examine temporal predictability between cereal yield and fertilizer consumption. Because the study relies on observational country-level data, the estimated coefficients are interpreted as conditional associations rather than structural causal effects.

Accordingly, the study addresses the following research questions:

1. Do fertilizer consumption, irrigated land, climatic conditions, and agricultural value added per worker exhibit a stable long-run relationship with cereal yield in Türkiye?
2. Are short-run changes in fertilizer consumption and irrigation capacity associated with changes in water stress, agricultural N_2O emissions, and agricultural value added per worker?
3. Does the temporal relationship between fertilizer consumption and cereal yield indicate potential reverse causality?

The study contributes to the literature in three ways. First, it provides a time-series assessment of agricultural productivity that explicitly accounts for stationarity and cointegration. Second, it extends the analysis beyond cereal output by directly incorporating water, environmental, and economic sustainability indicators. Third, it evaluates the robustness of the fertilizer–productivity relationship and examines its direction of temporal

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predictability. The use of publicly available annual data also enhances transparency, reproducibility, and the potential for future comparative research.

The remainder of the paper is organized as follows. The second section discusses the conceptual and empirical background relating to agricultural productivity, fertilizer use, irrigation, climate, and sustainable agriculture. The third section presents the data sources, variable measurements, econometric specifications, and estimation procedures. The fourth section reports the empirical findings, including the main productivity model, robustness analyses, Granger-causality results, and sustainability models. The final section discusses the principal findings, outlines policy implications, acknowledges the study's limitations, and identifies directions for future research.

2. Conceptual Background and Literature Review

Agricultural productivity is central to food security, rural development, and sustainable resource management. In many countries, including Türkiye, it is shaped by input use, irrigation capacity, climate conditions, land use patterns, and technological development. Cereal yield is often used as a key indicator of agricultural productivity because cereals are a major component of food systems and are highly sensitive to changes in input intensity, water availability, and environmental stress. Therefore, examining the relationship among cereal yield, fertilizer use, and irrigation capacity provides useful insights into productivity performance and sustainability challenges.

Fertilizer use is a key determinant of agricultural productivity. Fertilizers improve nutrient availability in the soil and can contribute to higher crop yields when applied efficiently. In the Turkish context, Aytekin and Keskin (2023) examined the relationship between fertilizer consumption and crop production using the ARDL bounds testing approach for the period 1976–2021. Their findings showed a positive and significant long-run relationship between fertilizer consumption and crop production. Specifically, they reported that a 1% increase in fertilizer consumption leads to approximately a 0.85% increase in crop production in the long run. This finding supports the argument that fertilizer use plays an important role in improving agricultural production in Türkiye.

Similarly, Gürbüz and Kadıoğlu (2023) analyzed grain production in Türkiye and its environmental drivers for the period 1988–2018. Their study found that fertilizer use and the number of tractors positively affect grain production, whereas greenhouse gas emissions have a negative effect. This finding is important for the present study because it confirms the productivity-enhancing role of agricultural inputs while also showing that environmental pressures can reduce agricultural performance. Therefore, productivity should be evaluated not only from an output-oriented perspective but also within a sustainability framework.

Although fertilizer use can contribute to productivity growth, excessive or inefficient use may pose environmental risks. Mavruk and Kocalar (2025) examined agricultural sustainability in Türkiye through nutrient use efficiency, particularly for nitrogen, phosphorus, and potassium. Their study emphasized that improving nutrient use efficiency is essential for sustainable agricultural production. This perspective is relevant to the present study because fertilizer consumption should not be interpreted solely as a productivity-enhancing factor; it should also be evaluated in terms of efficiency, soil protection, and environmental sustainability.

Water availability and irrigation capacity are also critical determinants of agricultural productivity. Irrigation reduces dependence on rainfall, improves yield stability, and supports production under climate variability. Oyeagu and Lewu (2025) emphasized the importance of agricultural water productivity for food security and sustainable farming systems. Their review highlights that water productivity can be improved through better management of water, nutrients, and agricultural practices in both irrigated and rain-fed systems. This supports including irrigated land as a key explanatory variable in the present study.

Research on sustainable water management further highlights the significance of efficient irrigation practices. Krishna & Ramu (2025) emphasize that techniques such as drip irrigation and rainwater harvesting can enhance crop productivity, particularly in areas experiencing climate variability and resource limitations. This conclusion aligns with the assertion that irrigation capacity is intrinsically connected to cereal productivity; however, the expansion of irrigation must be meticulously managed to prevent exerting excessive pressure on freshwater resources.

Climate change and extreme weather conditions further underscore the importance of water management in agriculture. Angın (2026) examined the effects of extreme climate events on the agriculture-water-energy nexus and emphasized that Türkiye's agriculture is vulnerable to climate-related water stress. This perspective is highly relevant because irrigation capacity is not only production infrastructure but also an adaptation mechanism against climate variability and water-related risks.

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Recent literature also highlights the role of precision agriculture and climate-smart practices in improving productivity and resource-use efficiency. Mushtaq et al. (2025) argued that integrating precision agronomy and climate-smart practices can enhance crop yields while improving resource efficiency. Their study emphasized technologies such as sensor-based irrigation and variable-rate nutrient application. These approaches are directly relevant to the present study because they show that fertilizer use and irrigation should be managed efficiently rather than simply increased.

Similarly, Poulik et al. (2025) highlighted the importance of tailored crop management approaches to improve agricultural productivity and sustainability. Their study emphasized that crop rotation, conservation tillage, and site-specific management practices can improve soil quality and strengthen resilience to climate variability. Although their study does not specifically analyze Türkiye, cereal yields, fertilizer consumption, or irrigated land, it supports the broader argument that sustainable agricultural productivity depends on efficient, context-specific input management.

In addition, Mohamed and Bakr (2025) examined technical efficiency in wheat cultivation by comparing fixed- and pivot-irrigation systems. Their findings showed that the rational use of water, seeds, and other production inputs can significantly improve wheat productivity. This study is relevant because it highlights the importance of irrigation systems and input efficiency in cereal-based production. It also supports the idea that productivity gains require not only increased input use but also better input management.

Utepov (2025) also emphasized the role of fertilizer consumption and irrigated land in agricultural production from an econometric perspective. The study reported that agricultural productivity, particularly cereal yield, is significantly affected by fertilizer consumption and irrigation-related variables. Although the study has a broader econometric focus, its findings are consistent with the present research model, which examines the effects of fertilizer use and irrigation capacity on cereal productivity.

Overall, the reviewed literature identifies fertilizer use and irrigation capacity as important agricultural inputs, while also emphasizing that productivity improvements must be evaluated alongside environmental sustainability, nutrient-use efficiency, water conservation, and climate adaptation. Existing studies on Türkiye have generally examined crop production, fertilizer efficiency, irrigation, or environmental pressures separately, leaving limited evidence on their combined productivity, economic, and environmental implications within a unified time-series framework. This study addresses that gap by investigating agricultural productivity, economic performance, and environmental sustainability in Türkiye over the period 1992–2022 using World Bank data. The empirical analysis combines unit-root tests, ARDL bounds testing and error-correction estimation, alternative model specifications, lagged-input and sub-period robustness analyses, and VAR-based Granger predictability tests. Separate first-difference models with Newey–West standard errors are also estimated for agricultural N_2O emissions, water stress, and agricultural value added per worker. By integrating these dimensions, the study provides a more comprehensive assessment of the productivity gains and sustainability trade-offs associated with fertilizer use and irrigation capacity.

3. Methodology

3.1. Research Design

This study employs a quantitative research design based on annual time-series data to investigate the relationships among agricultural productivity, agricultural input use, irrigation capacity, climatic conditions, and selected sustainability indicators in Türkiye. The primary analysis uses cereal yield as an indicator of agricultural productivity. Fertilizer consumption and irrigated agricultural land represent agricultural input intensity and irrigation capacity, respectively, while annual mean temperature, annual total precipitation, and agricultural value added per worker are included as control variables.

The study covers the period 1992–2022 and contains 31 annual observations. The study period was determined by the availability of consistent annual data across the variables included in the econometric analysis. In addition to the main agricultural productivity model, separate models are estimated for water stress, agricultural N_2O emissions, and agricultural value added per worker to examine the water-related, environmental, and economic dimensions of agricultural sustainability.

Because the analysis is based on observational country-level time-series data, the estimated coefficients are interpreted as conditional associations rather than structural causal effects. Potential reverse causality between cereal yield and fertilizer consumption is examined using lagged-input estimation and Granger-causality analysis. However, these procedures are treated as sensitivity checks and do not provide structural causal identification.

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3.2. Data Sources and Variable Measurement

The data were obtained from the World Bank's World Development Indicators and Climate Change Knowledge Portal databases. The initial dataset included cereal yield, fertilizer consumption, agricultural land, arable land, irrigated land, agricultural freshwater withdrawals, agriculture value added, food production index, water stress, agricultural N_2O emissions, renewable internal freshwater resources per capita, agricultural value added per worker, annual mean temperature, and annual total precipitation.

Cereal yield is measured in kilograms per hectare and is used as the dependent variable in the main agricultural productivity model. Fertilizer consumption is measured in kilograms per hectare of arable land, while irrigated land is expressed as a percentage of agricultural land. Annual mean temperature is measured in degrees Celsius, annual total precipitation in millimeters, and agricultural value added per worker in constant 2015 US dollars.

Water stress is expressed as the proportion of freshwater withdrawals relative to available renewable freshwater resources. Agricultural N_2O emissions are measured in million tonnes of CO_2 equivalent, while renewable internal freshwater resources per capita are measured in cubic meters.

Cereal yield, fertilizer consumption, irrigated land, annual total precipitation, agricultural value added per worker, water stress, agricultural N_2O emissions, and renewable internal freshwater resources per capita were transformed into natural logarithms. Annual mean temperature was retained in levels. The logarithmic transformations reduce scale differences and allow the coefficients of log-transformed variables to be interpreted as elasticities. Because temperature is measured in levels while cereal yield is expressed in logarithmic form, its coefficient is interpreted as a semi-elasticity. Variables included in the short-run sustainability models were subsequently expressed in logarithmic first differences.

The original average-precipitation indicator was excluded because it remained constant at 593 millimeters throughout the sample and therefore exhibited zero variance. Agricultural land, arable land, agriculture value added as a share of GDP, agricultural freshwater withdrawals, and the food production index were retained for descriptive purposes but were not included in the main econometric model. Their exclusion was based on theoretical parsimony, conceptual overlap with the selected variables, and the need to preserve degrees of freedom in a relatively small time-series sample.

3.3. Econometric Model Specification

The long-run agricultural productivity relationship underlying the ARDL model is specified as follows:

$$\ln CY_t = \beta_0 + \beta_1 \ln FERT_t + \beta_2 \ln IRRIG_t + \beta_3 TEMP_t + \beta_4 \ln PRECIP_t + \beta_5 \ln AVAW_t + \varepsilon_t$$

where $\ln CY_t$ denotes the natural logarithm of cereal yield, $\ln FERT_t$ represents fertilizer consumption, $\ln IRRIG_t$ denotes irrigated agricultural land, $TEMP_t$ represents annual mean temperature, $\ln PRECIP_t$ denotes annual total precipitation, and $\ln AVAW_t$ represents agricultural value added per worker.

Fertilizer consumption is expected to be positively associated with cereal yield because nutrient application may improve crop productivity. Irrigation capacity may also support agricultural productivity by improving water availability and reducing exposure to rainfall variability. However, irrigation outcomes may depend on water availability, irrigation efficiency, crop composition, and regional water-management conditions. Temperature and precipitation are included to control for annual climatic variation, while agricultural value added per worker captures broader changes in agricultural labor productivity, technological development, capital intensity, and production capacity.

Three additional models are specified to examine the short-run sustainability dimensions of agricultural activity. The water-sustainability model is expressed as:

$$\Delta \ln WSTRESS_t = \alpha_0 + \alpha_1 \Delta \ln IRRIG_t + \alpha_2 \Delta \ln RENEW_t + \alpha_3 \Delta \ln PRECIP_t + u_t$$

where $WSTRESS$ represents water stress and $RENEW$ represents renewable internal freshwater resources per capita.

The environmental-sustainability model is specified as:

$$\Delta \ln N2O_t = \gamma_0 + \gamma_1 \Delta \ln FERT_t + \gamma_2 \Delta \ln IRRIG_t + \gamma_3 \Delta \ln CY_t + v_t$$

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The economic-sustainability model is specified as:

$$\Delta \ln AVAW_t = \delta_0 + \delta_1 \Delta \ln CY_t + \delta_2 \Delta \ln FERT_t + \delta_3 \Delta \ln IRRIG_t + w_t$$

In these equations, Δdenotes the first-difference operator. Therefore, the coefficients of the sustainability models are interpreted as short-run elasticities rather than long-run equilibrium effects.

3.4. Econometric Estimation Procedure

The empirical analysis was conducted in several stages. First, descriptive statistics were calculated to summarize the distributional characteristics of the variables, including their minimum, maximum, mean, standard deviation, skewness, and excess kurtosis values. Pearson correlation coefficients were then estimated to examine preliminary associations among the variables included in the main productivity model. Because correlation coefficients do not control for common time trends or non-stationarity, they were not interpreted as causal or long-run econometric estimates.

Second, multicollinearity was assessed using variance inflation factors and tolerance statistics. The theoretically relevant explanatory variables were retained in the primary specification because their VIF values remained below the conventional threshold of 10. An alternative model containing a deterministic time trend was also examined. However, the trend specification produced substantially higher VIF values and was therefore treated only as a sensitivity analysis.

Third, the stationarity properties of the time-series variables were investigated using the Augmented Dickey–Fuller and Phillips–Perron unit-root tests. Tests for cereal yield, fertilizer consumption, irrigated land, agricultural value added per worker, water stress, renewable freshwater resources per capita, and agricultural N_2O emissions included a constant and deterministic trend at level. Tests for annual mean temperature and annual precipitation included a constant without a deterministic trend. Variables that were non-stationary at level were subsequently tested in first differences using a constant without a trend.

The unit-root results indicated that the variables included in the main productivity model were integrated of order zero or one and that none was integrated of order two. This combination supported the use of the autoregressive distributed lag bounds-testing approach.

For the main ARDL productivity analysis, the maximum lag length was restricted to one because the dataset contains only 31 annual observations. The Bayesian information criterion was used to select the primary specification because it favors parsimonious models in small samples. The Akaike information criterion was subsequently used as an alternative lag-selection criterion in the robustness analysis.

The existence of a long-run relationship was evaluated using the Pesaran–Shin–Smith bounds test under Case 3, which includes an unrestricted intercept but no deterministic trend. The null hypothesis of no level relationship was rejected when both the F-statistic and the t-statistic were more extreme than the corresponding upper-bound critical values. When cointegration was identified, the long-run coefficients and error-correction parameter were interpreted from the error-correction representation of the selected ARDL model. The BIC procedure selected an ARDL(1,0,0,0,0,0) specification for the main productivity model.

Post-estimation diagnostics included the Breusch–Godfrey LM test for serial correlation, the Breusch–Pagan/Cook–Weisberg test for heteroskedasticity, the Ramsey RESET test for functional-form misspecification, and the skewness–kurtosis test for residual normality. Parameter stability was assessed using the cumulative-sum test. Variance inflation factors were also examined to evaluate multicollinearity.

3.5. Robustness and Sensitivity Analyses

Several additional estimations were conducted to assess the robustness of the main productivity findings. First, the ARDL model was re-estimated using the Akaike information criterion instead of the Bayesian information criterion. Second, a Newey–West specification incorporating one-year-lagged fertilizer consumption and irrigated land was estimated to reduce concerns about contemporaneous reverse causality. Third, an alternative model containing a deterministic time trend was examined. Because the trend specification generated substantial multicollinearity, it was not used for substantive inference.

Fourth, separate Newey–West estimations were conducted for the 1992–2007 and 2008–2022 sub-periods. Because the two sub-periods contain only 15–16 observations, these results were treated as exploratory sensitivity analyses rather than as formal evidence of structural breaks.

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Newey–West standard errors were calculated using a lag-truncation parameter of one. The method was employed to provide inference that is robust to potential heteroskedasticity and serial correlation in the annual time-series data.

3.6. Endogeneity and Granger-Causality Analysis

Potential reverse causality between cereal yield and fertilizer consumption was further examined using a bivariate vector autoregression model. Because the natural logarithms of cereal yield and fertilizer consumption were stationary at level, both variables were included in the VAR model in levels.

The optimal lag length was evaluated using the likelihood-ratio statistic, final prediction error, Akaike information criterion, Hannan–Quinn information criterion, and Schwarz Bayesian information criterion. All criteria supported a two-lag specification, and a VAR(2) model was therefore estimated.

Before conducting the Granger-causality Wald tests, the VAR model was evaluated using the eigenvalue stability condition and residual Lagrange-multiplier autocorrelation tests. The model satisfied the stability condition because all eigenvalues were located inside the unit circle. The residual LM tests were used to verify the absence of residual autocorrelation at the first and second lag orders.

Granger causality was interpreted as temporal predictability rather than structural economic causality. Therefore, the results were used only as an endogeneity sensitivity check. In the absence of a theoretically valid and consistently measured external instrumental variable for the entire study period, an instrumental-variable model was not estimated.

3.7. Sustainability-Model Estimation

The stationarity properties of the variables included in the sustainability models were examined using the same ADF and Phillips–Perron testing procedures. The results indicated that water stress, renewable internal freshwater resources per capita, and agricultural N_2O emissions were non-stationary at level but stationary after first differencing.

ARDL bounds tests were initially conducted for the water-stress, agricultural N_2O-emissions, and economic-sustainability specifications. However, the tests did not provide evidence of stable long-run relationships at the 5% significance level. Consequently, the three sustainability models were estimated in logarithmic first differences using Newey–West standard errors with a lag-truncation parameter of one.

The coefficients obtained from these models represent short-run elasticities. The substantive coefficients and statistical significance levels reported in the Findings section are based on the Newey–West estimations.

The corresponding OLS specifications containing the same dependent and explanatory variables were estimated solely for diagnostic purposes. The Breusch–Godfrey, Breusch–Pagan/Cook–Weisberg, Ramsey RESET, VIF, skewness–kurtosis normality, and CUSUM tests were applied to these corresponding OLS models because the full set of post-estimation diagnostic commands was not directly available after the Newey–West estimations.

3.8. Data-Quality Procedures

Before estimation, the dataset was examined for missing observations, duplicate years, zero-variance indicators, and potentially extreme values. No duplicate years or missing observations were identified among the variables included in the final models.

Standardized values were calculated to screen for potentially extreme observations. No observations with absolute z-scores greater than three were identified. The constant average-precipitation indicator was excluded because it contained no annual variation.

The agricultural freshwater-withdrawal observation of 100% recorded for 2021 was flagged during the descriptive screening. Because agricultural freshwater withdrawals were not included in the final productivity or sustainability regression models, this observation did not affect the estimated coefficients. No observations were removed solely because of their distributional position.

3.9. Software

The statistical analyses were conducted using SPSS and Stata. SPSS was used primarily for initial data screening, descriptive statistics, and Pearson correlation analysis. Stata was used for logarithmic transformations, multicollinearity diagnostics, ADF and Phillips–Perron unit-root tests, ARDL estimation,

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bounds testing, error-correction estimation, Newey–West regressions, VAR lag-order selection, VAR stability and residual-autocorrelation testing, Granger-causality Wald tests, robustness analyses, and post-estimation diagnostic and stability tests.

4. Findings

Table 1. Descriptive Statistics

Variable	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis
Cereal yield	1,922.30	3,464.70	2,655.06	458.79	0.177	−1.307
Fertilizer consumption	61.01	149.64	96.30	22.08	0.678	−0.107
Agricultural land	49.01	53.56	51.11	1.45	0.250	−1.165
Arable land	25.44	32.10	28.93	2.48	−0.048	−1.775
Irrigated land	7.64	12.13	9.04	1.28	1.111	0.623
Agricultural freshwater withdrawals	72.47	100.00	83.31	5.21	0.497	2.570
Agriculture value added	5.70	15.46	9.04	2.77	1.052	0.407
Food production index	60.40	128.92	85.53	19.95	0.577	−0.739
Water stress	23.47	47.89	33.85	7.66	0.444	−1.123
Agricultural N_2O emissions	13.58	23.03	16.40	2.58	1.101	0.118
Renewable internal freshwater resources per capita	2,671.22	3,914.46	3,224.94	364.57	0.195	−1.005
Agricultural value added per worker	4,241.73	14,311.78	8,272.33	3,174.41	0.218	−1.056
Annual mean temperature	9.30	13.38	11.77	0.87	−0.539	1.124
Annual total precipitation	543.58	825.20	697.11	61.56	−0.207	0.112
Time trend	1.00	31.00	16.00	9.09	0.000	−1.200

Note: N = 31 annual observations. Cereal yield is measured in kilograms per hectare; fertilizer consumption is measured in kilograms per hectare of arable land; agricultural land, arable land, irrigated land, agricultural freshwater withdrawals, agriculture value added, and water stress are expressed as percentages. Agricultural N_2O emissions are measured in Mt CO_2 equivalent. Renewable internal freshwater resources per capita are measured in cubic meters. Agricultural value added per worker is measured in constant 2015 US dollars. Annual mean temperature is measured in degrees Celsius, and annual total precipitation is measured in millimeters. The time-trend variable ranges from 1 for 1992 to 31 for 2022. The original average precipitation indicator was excluded because it remained constant at 593 mm and exhibited zero variance.

Table 1 presents the descriptive statistics for the agricultural productivity, input-use, land-use, water-resource, environmental sustainability, economic performance, and climate variables used in the study. The dataset consists of 31 annual observations for Türkiye covering the period 1992–2022.

Cereal yield ranged from 1,922.30 to 3,464.70 kg per hectare, with a mean of 2,655.06 kg per hectare and a standard deviation of 458.79. These figures demonstrate considerable variation in cereal productivity during the study period. Fertilizer consumption averaged 96.30 kg per hectare of arable land and ranged between 61.01 and 149.64, indicating substantial variation in agricultural input intensity. Irrigated agricultural land had a mean value of 9.04%, increasing from a minimum of 7.64% to a maximum of 12.13%. Agricultural land represented an average of 51.11% of total land area, whereas arable land accounted for an average of 28.93%.

The water-resource indicators reveal considerable pressure on Türkiye's freshwater resources. Agricultural freshwater withdrawals averaged 83.31% of total freshwater withdrawals and ranged from 72.47% to 100%. The relatively high kurtosis value of this variable may reflect the influence of the 100% observation recorded in 2021. Consequently, this observation is examined carefully in the subsequent data-quality and sensitivity analyses. The level of water stress ranged from 23.47% to 47.89%, with an average of 33.85%. Renewable internal freshwater resources per capita ranged from 2,671.22 to 3,914.46 cubic meters, with a mean of 3,224.94 cubic meters.

Agricultural N_2O emissions averaged 16.40 Mt CO_2 equivalent and varied between 13.58 and 23.03 Mt CO_2 equivalent. The inclusion of this variable extends the analysis beyond agricultural output by enabling an assessment of the environmental pressures associated with agricultural input use. The positive skewness of agricultural N_2O emissions indicates that relatively high emission values occurred in a smaller number of observations, particularly toward the later years of the study period.

The economic indicators also displayed substantial variation. Agricultural value added per worker ranged from USD 4,241.73 to USD 14,311.78 at constant 2015 prices, with an average of USD 8,272.33. Its comparatively large standard deviation of USD 3,174.41 suggests considerable changes in agricultural labor productivity

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during the study period. Agriculture value added as a share of GDP averaged 9.04%, while the food production index ranged from 60.40 to 128.92 and had a mean value of 85.53.

The annual mean temperature varied between 9.30°C and 13.38°C, with an average of 11.77°C. Annual total precipitation ranged from 543.58 to 825.20 mm and averaged 697.11 mm. Unlike the original average precipitation indicator, these variables provide annual variation and can therefore be used to control for climatic conditions in the econometric analysis. The original average precipitation series remained constant at 593 mm throughout the entire period and was consequently excluded from the correlation, unit-root, multicollinearity, and regression analyses.

The skewness and kurtosis statistics generally indicate moderate distributional asymmetry rather than severe deviations. Irrigated land, agriculture value added, and agricultural N_2O emissions exhibit relatively greater positive skewness, while agricultural freshwater withdrawals display the highest kurtosis. However, descriptive distributional statistics do not determine whether time-series variables are stationary. Therefore, unit-root tests are conducted before estimating the econometric models.

Table 2. Pearson Correlation Analysis Results

Variable	1	2	3	4	5	6
1. Cereal yield	1.000					
2. Fertilizer consumption	0.865***	1.000				
3. Irrigated land	0.845***	0.807***	1.000			
4. Annual mean temperature	0.527***	0.529***	0.599***	1.000		
5. Annual total precipitation	−0.060	−0.068	−0.170	0.101	1.000	
6. Agricultural value added per worker	0.933***	0.821***	0.898***	0.597***	−0.122	1.000

Note: N = 31. Variables 1, 2, 3, 5, and 6 are expressed in natural logarithms. Variable 4 is measured in levels. ***p < 0.01.

Table 2 presents the Pearson correlation coefficients among the variables included in the cereal productivity model. Cereal yield is strongly and positively correlated with fertilizer consumption (r = 0.865, p < 0.01), irrigated land (r = 0.845, p < 0.01), and agricultural value added per worker (r = 0.933, p < 0.01). These results indicate that higher cereal productivity is associated with greater fertilizer intensity, expanded irrigation capacity, and higher agricultural labor productivity.

Annual mean temperature is moderately and positively correlated with cereal yield (r = 0.527, p < 0.01), fertilizer consumption (r = 0.529, p < 0.01), irrigated land (r = 0.599, p < 0.01), and agricultural value added per worker (r = 0.597, p < 0.01). By contrast, annual total precipitation is not significantly correlated with cereal yield or the other explanatory variables.

The matrix also reveals relatively high correlations among several explanatory variables. In particular, irrigated land is strongly correlated with agricultural value added per worker (r = 0.898, p < 0.01), while fertilizer consumption is strongly correlated with both agricultural value added per worker (r = 0.821, p < 0.01) and irrigated land (r = 0.807, p < 0.01). These coefficients suggest a potential multicollinearity problem in the extended regression specification. Therefore, variance inflation factor and tolerance statistics are examined before estimating the final model.

These correlations should be interpreted as preliminary associations rather than causal effects. Moreover, because several variables exhibit common long-term trends, the correlation coefficients may partly reflect non-stationary time-series behavior. Unit-root tests are therefore conducted before the ARDL and cointegration analyses.

Table 3. Multicollinearity Diagnostic Results

Variable	VIF	Tolerance
Fertilizer consumption	3.36	0.298
Irrigated land	5.98	0.167
Annual mean temperature	1.71	0.584
Annual total precipitation	1.11	0.899
Agricultural value added per worker	6.08	0.164
Mean VIF	**3.65**	—

Note: The dependent variable is the natural logarithm of cereal yield. VIF denotes the variance inflation factor, while tolerance is calculated as $1/VIF$.

Variance inflation factor and tolerance statistics were calculated to assess whether the extended productivity model was affected by multicollinearity. As shown in Table 3, the VIF values ranged from 1.11 to 6.08, with a

DEMETER: Journal of Farming and Agriculture
Vol 4, Issue 1, March 2026, Page 320-334
ISSN: 2987-5889 (Media Online)
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mean VIF of 3.65. Fertilizer consumption, annual mean temperature, and annual total precipitation exhibited VIF values below 5. Irrigated land and agricultural value added per worker produced moderately higher VIF values of 5.98 and 6.08, respectively, with corresponding tolerance values of 0.167 and 0.164.

Although these results indicate moderate collinearity between irrigation capacity and agricultural labor productivity, none of the VIF values exceeded the commonly used threshold of 10. Therefore, the variables were retained in the main specification. Nevertheless, the coefficients of irrigated land and agricultural value added per worker should be interpreted cautiously because their relatively high correlation may increase the standard errors of the estimated coefficients.

An alternative model replacing agricultural value added per worker with a deterministic time trend was also examined. However, the time-trend variable produced a VIF value of 12.18 and a tolerance value of 0.082, while the VIF of irrigated land increased to 8.77. Consequently, the time-trend specification was not adopted as the main model and was retained only as a robustness check.

Table 4. ADF and Phillips–Perron Unit-Root Test Results

Variable	**ADF level**	**PP level**	**ADF first difference**	**PP first difference**	**Order**
Log cereal yield	−3.514**	−5.767***	—	—	I(0)
Log fertilizer consumption	−5.395***	−4.522***	—	—	I(0)
Log irrigated land	−1.219	−1.404	−5.414***	−5.415***	I(1)
Annual mean temperature	−3.354**	−4.691***	—	—	I(0)
Log annual total precipitation	−4.141***	−5.264***	—	—	I(0)
Log agricultural value added per worker	−2.120	−2.146	−6.168***	−6.140***	I(1)

Note: The ADF and PP tests for cereal yield, fertilizer consumption, irrigated land, and agricultural value added per worker include a constant and deterministic trend at level. Tests for annual mean temperature and annual precipitation include a constant without a trend. First-difference tests include a constant without a deterministic trend. **p < 0.05; ***p < 0.01.

Before estimating the time-series models, the stationarity properties of the variables were examined using the Augmented Dickey–Fuller and Phillips–Perron unit-root tests. The results presented in Table 4 indicate a mixture of level-stationary and first-difference-stationary variables.

The natural logarithms of cereal yield and fertilizer consumption were stationary at level. Annual mean temperature and the natural logarithm of annual total precipitation were also found to be stationary at level. The ADF result for cereal yield was relatively close to the 5% critical value; however, the MacKinnon probability value and the Phillips–Perron test provided evidence in favor of level stationarity.

In contrast, the natural logarithms of irrigated land and agricultural value added per worker failed to reject the unit-root null hypothesis at level. Both variables became stationary after first differencing and were therefore classified as integrated of order one, I(1).

Overall, the variables were found to be either I(0) or I(1), and none was integrated of order two. This integration structure supports the use of the ARDL bounds-testing approach to investigate whether a stable long-run relationship exists among cereal yield, fertilizer consumption, irrigation capacity, climate conditions, and agricultural labor productivity.

Table 5. ARDL Long-Run and Error-Correction Results

Component	**Variable**	**Coefficient**	**Std. Error**	**t**	**p-value**
Adjustment	ECT_{t-1}	−0.935	0.202	−4.64	<0.001
Long run	Fertilizer consumption	0.254	0.097	2.61	0.016
Long run	Irrigated land	−0.031	0.217	−0.14	0.888
Long run	Annual mean temperature	−0.026	0.027	−0.97	0.341
Long run	Annual total precipitation	0.111	0.138	0.81	0.429
Long run	Agricultural value added per worker	0.324	0.075	4.32	<0.001
Short run	Constant	3.243	1.149	2.82	0.010

Note: Selected specification is ARDL(1,0,0,0,0,0), based on the Bayesian information criterion. The dependent variable is the first difference of the natural logarithm of cereal yield in the error-correction representation. N = 30.

DEMETER: Journal of Farming and Agriculture
Vol 4, Issue 1, March 2026, Page 320-334
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Table 6. ARDL Bounds-Test Results

Test	Statistic	5% I(0) bound	5% I(1) bound	Decision
F-bounds test	6.585	3.199	4.669	Cointegration
t-bounds test	−4.637	−2.932	−4.312	Cointegration

Note: Critical values are finite-sample values for five explanatory variables and 30 observations under Case 3. The null hypothesis states that no level relationship exists.

Given that the variables were integrated of order zero or one and none was integrated of order two, the ARDL bounds-testing approach was employed. Based on the Bayesian information criterion and a maximum lag length of one, the ARDL(1,0,0,0,0,0) specification was selected.

The bounds-test results provide evidence of a stable long-run relationship among cereal yield, fertilizer consumption, irrigated land, climatic conditions, and agricultural value added per worker. The calculated F-statistic of 6.585 exceeds the 5% upper-bound critical value of 4.669. Similarly, the t-statistic of −4.637 is more negative than the corresponding 5% upper-bound critical value of −4.312. The null hypothesis of no level relationship is therefore rejected at the 5% significance level. However, the result remains inconclusive at the 1% level.

The error-correction coefficient is negative and statistically significant (ECT = −0.935, $p < 0.001$), confirming the stability of the long-run relationship. Its magnitude indicates that approximately 93.5% of a deviation from the long-run equilibrium is corrected within one year.

The long-run results indicate that fertilizer consumption has a positive and statistically significant association with cereal yield. A 1% increase in fertilizer consumption is associated with an approximately 0.254% increase in cereal yield, holding the remaining variables constant. Agricultural value added per worker also has a positive and statistically significant coefficient. A 1% increase in agricultural value added per worker is associated with an approximately 0.324% increase in cereal yield.

In contrast, the coefficient of irrigated land is statistically insignificant. Annual mean temperature and annual total precipitation also do not exhibit statistically significant long-run relationships with cereal yield. These results indicate that the previously reported positive effect of irrigated land is not robust to the inclusion of climatic and economic controls and the application of an appropriate time-series specification. Accordingly, the results should not be interpreted as evidence that irrigation expansion has a direct negative effect on cereal productivity; rather, the analysis does not identify a statistically distinguishable long-run effect during the study period.

Table 7. Diagnostic Test Results for the ARDL Model

Diagnostic test	Null hypothesis	Test statistic	p-value	Decision
Breusch–Godfrey LM	No serial correlation	$\chi^2(1) = 0.642$	0.423	Do not reject H_0
Breusch–Pagan/Cook–Weisberg	Constant error variance	$\chi^2(1) = 0.010$	0.937	Do not reject H_0
Ramsey RESET	No model-specification error	$F(3,20) = 0.140$	0.935	Do not reject H_0
Skewness–Kurtosis normality test	Residuals are normally distributed	$\chi^2(2) = 1.030$	0.598	Do not reject H_0
CUSUM stability test	No structural break	Statistic = 0.343	—	Stable at the 5% level

Note: The 5% critical value for the CUSUM test is 0.948. Since the calculated statistic is below the critical value, the null hypothesis of parameter stability cannot be rejected.

A series of diagnostic tests was conducted to assess the adequacy of the selected ARDL(1,0,0,0,0,0) model. The Breusch–Godfrey LM test produced a probability value of 0.423, indicating that the null hypothesis of no serial correlation could not be rejected. Therefore, the residuals do not exhibit statistically significant first-order autocorrelation.

The Breusch–Pagan/Cook–Weisberg test yielded a probability value of 0.937. This result indicates that the null hypothesis of constant error variance could not be rejected and that the model does not exhibit evidence of heteroskedasticity. Accordingly, the use of conventional ARDL standard errors is supported by the diagnostic results.

DEMETER: Journal of Farming and Agriculture
Vol 4, Issue 1, March 2026, Page 320-334
ISSN: 2987-5889 (Media Online)
DOI: https://doi.org/10.58905/demeter.v4i1.747

The Ramsey RESET test was used to assess potential functional-form misspecification and omitted nonlinear relationships. The test was statistically insignificant (F = 0.140, p = 0.935), providing no evidence of a model-specification error. In addition, the joint skewness–kurtosis test was insignificant (χ^2 = 1.030, p = 0.598), indicating that the normality assumption of the residuals could not be rejected.

Finally, parameter stability was examined using the cumulative-sum test. The calculated CUSUM statistic of 0.343 was below the 5% critical value of 0.948. Therefore, the null hypothesis of parameter stability could not be rejected. Overall, the diagnostic findings indicate that the estimated ARDL model is free from serial correlation, heteroskedasticity, major functional-form misspecification, non-normal residual behavior, and structural instability.

Table 8. Robustness and Sensitivity Analysis

Model	Fertilizer	Irrigated land	Temperature	Precipitation	AVA per worker
BIC-ARDL long run	0.254**	−0.031	−0.026	0.111	0.324***
AIC-ARDL long run	0.223**	−0.013	−0.023	0.297	0.333***
Lagged-input Newey–West	0.158	−0.064	−0.031*	0.206	0.386***
1992–2007	0.345***	−0.074	−0.004	0.404*	0.232***
2008–2022	0.249*	−0.712	−0.052	−0.035	0.699

Note: The BIC- and AIC-based estimates represent long-run ARDL coefficients. In the lagged-input Newey–West model, fertilizer consumption and irrigated land enter with one-year lags. The sub-period estimates are based on Newey–West standard errors. Since both the dependent variable and most continuous explanatory variables are expressed in natural logarithms, their coefficients are interpreted as elasticities. The temperature coefficient is a semi-elasticity because temperature is measured in levels. ***p < 0.01, **p < 0.05, *p < 0.10. Sub-period results should be interpreted as exploratory because each period contains only 15–16 observations.

Table 8 presents the robustness and sensitivity analyses conducted using alternative lag-selection criteria, lagged input variables, and sub-period estimations. The long-run results are broadly consistent across the BIC- and AIC-based ARDL specifications. Fertilizer consumption remains positive and statistically significant in both models, with estimated long-run elasticities of 0.254 and 0.223, respectively. Similarly, agricultural value added per worker retains a positive and highly significant coefficient in both specifications. These findings indicate that the positive long-run associations of fertilizer use and agricultural labor productivity with cereal yield are not sensitive to the choice between the Bayesian and Akaike information criteria.

In contrast, irrigated land remains statistically insignificant in both ARDL specifications. Annual mean temperature and annual precipitation are also insignificant in the long-run models. Therefore, the analysis does not provide robust evidence that irrigation expansion or annual climatic variation had a statistically distinguishable long-run association with cereal yield during the study period after fertilizer use and agricultural value added per worker were controlled for.

The lagged-input Newey–West specification provides a more cautious assessment of the fertilizer–yield relationship. The coefficient of lagged fertilizer consumption remains positive but is not statistically significant at conventional levels. Lagged irrigated land is also insignificant, whereas agricultural value added per worker remains positive and statistically significant. The weaker fertilizer result suggests that its estimated relationship with cereal yield is less precisely identified when prior-year input use is considered. This finding is consistent with the need to interpret the fertilizer coefficient as a conditional association rather than a strictly causal effect.

The exploratory sub-period results indicate some variation over time. During 1992–2007, fertilizer consumption and agricultural value added per worker are positive and statistically significant, while precipitation is positive at the 10% significance level. During 2008–2022, the fertilizer coefficient remains positive but is significant only at the 10% level, and the remaining coefficients are statistically insignificant. The decline in statistical significance in the later period may reflect changes in the underlying agricultural production structure, diminishing marginal returns to agricultural inputs, or the limited statistical power associated with the small sub-period sample.

Overall, the robustness analyses support the positive long-run relationships of fertilizer consumption and agricultural value added per worker with cereal yield under alternative ARDL lag-selection criteria. However, the fertilizer relationship becomes weaker in the lagged-input and later-period specifications. Moreover, the coefficient of irrigated land is not robustly significant across any of the reported models. Accordingly, the revised findings are presented as conditional and time-sensitive associations rather than universal causal effects.

DEMETER: Journal of Farming and Agriculture
Vol 4, Issue 1, March 2026, Page 320-334
ISSN: 2987-5889 (Media Online)
DOI: https://doi.org/10.58905/demeter.v4i1.747

Table 9. Granger-Causality Wald Test Results

Null hypothesis	χ^2	df	p-value	Decision
Fertilizer consumption does not Granger-predict cereal yield	3.699	2	0.157	Do not reject
Cereal yield does not Granger-predict fertilizer consumption	21.952	2	<0.001	Reject

Note: The results are based on a stable bivariate VAR(2) model estimated with 29 annual observations. The residual LM tests indicate no autocorrelation at lag 1 (p = 0.112) or lag 2 (p = 0.749). Granger causality represents temporal predictability and should not be interpreted as structural economic causality.

A bivariate VAR model was estimated to examine the direction of temporal predictability between cereal yield and fertilizer consumption. The lag-selection criteria identified two annual lags as the optimal specification. The estimated VAR(2) model satisfied the stability condition, as all eigenvalues were located inside the unit circle. Moreover, the Lagrange-multiplier tests did not indicate residual autocorrelation at either the first lag (p = 0.112) or the second lag (p = 0.749).

The Granger-causality results indicate that the null hypothesis that fertilizer consumption does not Granger-predict cereal yield cannot be rejected ($\chi^2 = 3.699$, $p = 0.157$). In contrast, the null hypothesis that cereal yield does not Granger-predict fertilizer consumption is rejected ($\chi^2 = 21.952$, $p < 0.001$). Therefore, the results indicate unidirectional temporal predictability from cereal yield to fertilizer consumption. This finding suggests that improvements in cereal productivity may precede subsequent increases in fertilizer use and that reverse causality cannot be ruled out. Accordingly, the fertilizer coefficient in the main ARDL model is interpreted as a conditional long-run association rather than a structural causal effect.

Table 10. Short-Run Sustainability Model Results

Explanatory variable	Water stress	Agricultural N_2O emissions	Agricultural value added per worker
Δ Log irrigated land	−0.095	0.049	−0.686*
Δ Log renewable freshwater resources per capita	−1.869	—	—
Δ Log annual precipitation	0.037	—	—
Δ Log fertilizer consumption	—	0.353***	0.152**
Δ Log cereal yield	—	−0.032	0.430***
Constant	0.001	0.005	0.040**
Observations	30	30	30
Model p-value	0.278	<0.001	<0.001

Note: Models are estimated in first differences using Newey–West standard errors with a maximum lag of one. The coefficients are interpreted as short-run elasticities. ***p < 0.01, **p < 0.05, *p < 0.10.

Table 10 presents the short-run sustainability results estimated in first differences with Newey–West standard errors. The water-stress model is not jointly significant (p = 0.278), and none of the explanatory variables has a statistically significant coefficient. Therefore, annual changes in irrigated land, renewable freshwater resources per capita, and precipitation do not provide sufficient evidence to explain short-run changes in water stress during the study period.

In the environmental model, fertilizer consumption has a positive and statistically significant association with agricultural N_2O emissions. A 1% increase in fertilizer consumption is associated with an approximately 0.353% increase in N_2O emissions in the short run. Changes in irrigated land and cereal yield are statistically insignificant. In the economic model, a 1% increase in cereal yield is associated with an approximately 0.430% increase in agricultural value added per worker, while a 1% increase in fertilizer consumption is associated with an approximately 0.152% increase. The irrigated-land coefficient is negative but significant only at the 10% level and should therefore be interpreted cautiously. Overall, the results suggest that fertilizer use may contribute to short-run economic performance while simultaneously increasing environmental pressure through higher N_2O emissions.

Table 11. Diagnostic Tests for the Sustainability Models

Diagnostic test	Water-stress model	N_2O model	Economic model
Breusch–Godfrey p-value	0.208	0.608	0.082
Breusch–Pagan p-value	0.443	0.375	0.072
Ramsey RESET p-value	0.858	0.472	0.530
Normality-test p-value	0.007	0.830	0.182

Mean VIF	1.05	1.11	1.11
CUSUM statistic	0.308	0.661	0.635
Stability at 5%	Stable	Stable	Stable

Note: The 5% critical value of the CUSUM statistic is 0.948. Newey–West estimates are reported in Table 10, while the diagnostic tests are based on the corresponding OLS specifications.

Table 11 reports the diagnostic-test results for the three sustainability models. The Breusch–Godfrey, Breusch–Pagan, and Ramsey RESET tests are statistically insignificant at the 5% level in all models, indicating no strong evidence of serial correlation, heteroskedasticity, or functional-form misspecification. Mean VIF values are close to one, showing that multicollinearity is not a concern. The CUSUM statistics are also below the 5% critical value, supporting parameter stability throughout the estimation period.

Residual normality is satisfied in the N_2O-emissions and economic-sustainability models but rejected in the water-stress model. Consequently, the water-stress findings should be interpreted more cautiously, particularly because the model is not jointly significant. The economic model's serial-correlation and heteroskedasticity p-values are relatively close to the 10% threshold, although they remain insignificant at the 5% level. The use of Newey–West standard errors provides additional protection against these potential concerns.

5. Conclusion

This study examined the relationships among agricultural productivity, fertilizer consumption, irrigation capacity, climatic conditions, and selected sustainability indicators in Türkiye over the period 1992–2022. Using annual World Bank data, the analysis combined unit-root testing, the ARDL bounds-testing approach, diagnostic and robustness tests, Granger-causality analysis, and short-run Newey–West sustainability models.

The results provide evidence of a stable long-run relationship in the cereal-productivity model. Fertilizer consumption and agricultural value added per worker are positively and significantly associated with cereal yield. A 1% increase in fertilizer consumption is associated with an approximately 0.254% increase in cereal yield in the long run, while a 1% increase in agricultural value added per worker is associated with an approximately 0.324% increase. The negative and significant error-correction coefficient indicates that approximately 93.5% of deviations from long-run equilibrium are corrected within one year.

In contrast, irrigated land does not exhibit a statistically significant long-run relationship with cereal yield after climatic and economic controls are included. Annual mean temperature and annual precipitation are also statistically insignificant. Therefore, the findings do not support the earlier conclusion that irrigation expansion independently increases cereal productivity. Rather, irrigation outcomes may depend on water-use efficiency, crop composition, regional conditions, infrastructure quality, and the effective utilization of irrigation capacity.

The robustness analyses broadly confirm the positive long-run associations of fertilizer consumption and agricultural value added per worker under alternative ARDL lag-selection criteria. However, the fertilizer coefficient becomes weaker when prior-year input use is considered. In addition, the Granger-causality results indicate temporal predictability from cereal yield to fertilizer consumption, but not from fertilizer consumption to cereal yield. This finding suggests that higher productivity may encourage subsequent fertilizer investment and that reverse causality cannot be ruled out. The estimated coefficients should therefore be interpreted as conditional associations rather than structural causal effects.

The sustainability models reveal an important economic–environmental trade-off. Short-run increases in fertilizer consumption are positively associated with agricultural N_2O emissions and agricultural value added per worker. Specifically, a 1% increase in fertilizer consumption is associated with an approximately 0.353% increase in N_2O emissions and a 0.152% increase in agricultural value added per worker. Cereal yield is also positively associated with agricultural value added per worker. By contrast, the water-stress model does not identify statistically significant short-run relationships with irrigated land, renewable freshwater resources per capita, or precipitation.

These findings support policies that focus on improving fertilizer-use efficiency rather than simply increasing fertilizer application. Soil testing, precision nutrient management, balanced fertilization, farmer training, and improved monitoring of nitrogen losses may help preserve productivity gains while reducing emissions. Irrigation policies should similarly emphasize efficient water allocation, modern irrigation technologies, infrastructure maintenance, and region-specific water management rather than expansion of irrigated area alone.

The study has several limitations. It relies on a relatively small national-level annual dataset and cannot capture regional, crop-specific, seasonal, or farm-level differences. Potential endogeneity also remains because a valid external instrument was unavailable for the full study period. Future research should use regional panel data, crop-level observations, fertilizer-price or policy shocks, measures of irrigation efficiency, and nonlinear or structural-break models. Overall, sustainable agricultural productivity in Türkiye requires an integrated policy approach that combines productivity improvement with fertilizer efficiency, water conservation, emissions reduction, and stronger agricultural labor productivity.

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