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RESEARCH ARTICLE
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Irrigation Water Effects on Crop Self-sufficiency and Sustainability: A Regression Modelling for Arid Agricultural Regions

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ABSTRACT

Jordan's agricultural sector faces intensifying water scarcity, placing strategic pressure on key food crops such as tomato, which accounts for 35.1% of national crop production. This study analyzed sixteen years of production and water quality data (2008–2023) from the Jordan Valley to evaluate tomato self-sufficiency responses to freshwater and blended treated wastewater (TWW) irrigation. Stepwise regression, supported by ADF stationarity testing, was applied to quantify the dependency of tomato productivity on irrigation water quantity and quality indicators, including salinity and chloride concentrations. Results show that tomato self-sufficiency remains structurally stable over time, despite significant variation in water quality. A clear negative association was observed between self-sufficiency and rising chloride levels in blended wastewater, whereas overall electrical conductivity remained comparatively stable. Years of highest self-sufficiency coincided with the lowest chloride concentrations, indicating chloride, not bulk salinity, as the emerging limiting factor. These findings align with recent studies highlighting chloride-driven yield decline under wastewater irrigation. Tomato exhibited higher resilience than other staple crops, maintaining productive capacity even under declining freshwater availability. The study demonstrates that crop-specific irrigation standards, rather than uniform water allocation policies, could enable significant freshwater savings while preserving national food security. Integrating chloride monitoring thresholds, improving TWW management, and supporting farmer training and breeding programs can further enhance climate resilience. The outcomes directly support progress toward SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production) by promoting efficient water reuse and resilient food production systems under water scarcity.

Keywords: Chloride accumulation, Food security resilience, Salinity stress, Sustainable Development Goals (SDGs), Treated wastewater reuse.

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INTRODUCTION

Water scarcity is increasingly recognized as one of the most critical global challenges, particularly in arid and semi-arid regions where freshwater (FW) resources are inherently limited. By 2025, approximately 1.8 billion people are expected to live under conditions of severe water stress, driven by population growth, climate change, urbanization and escalating demand from agricultural, industrial and domestic sectors (Muscarella et al., 2024; El-Mahroug et al., 2025; Hussaini et al., 2025). This growing imbalance between water availability and demand poses profound risks to agricultural productivity, food security, and socioeconomic stability. Water is fundamental to both human survival and food systems, and any disruption in its availability directly affects national resilience and supply chains. Agriculture alone accounts for nearly 80% of global FW withdrawals, and without improvements in efficiency and alternative water sources, irrigation expansion in water-stressed regions will further intensify scarcity (Hamaideh et al., 2024; Chang, 2025).

The strong dependence of agriculture on water raises serious concerns regarding long-term sustainability under increasing hydrological stress. Irrigation demand is

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expected to rise as climate variability intensifies and rainfall becomes more erratic, particularly in arid environments (Darwish & Talozi, 2024; Biswas et al., 2025). In response, treated wastewater (TWW) reuse has emerged as a key adaptation strategy, offering a reliable and climate-resilient water source capable of partially offsetting FW deficits (Obeidat et al., 2025). Beyond augmenting water quantity, TWW often contains nutrients that can reduce fertilizer inputs and production costs. Nevertheless, concerns related to salinity, ion toxicity, and long-term soil degradation remain major barriers to its optimal use, especially where irrigation guidelines rely on generalized water quality indicators (Imtaiz, 2025; Ashraf & Khalid, 2025).

Jordan exemplifies the severity of water scarcity at the national scale. The country is consistently ranked among the most water-scarce nations globally, with per-capita FW availability declining from approximately 145m³ yr⁻¹ in 2017 to a projected 80m³ yr⁻¹ by 2025 (Abu-Awwad, 2021). This situation is compounded by low and highly variable rainfall, rapid population growth—reaching nearly 11 million inhabitants in 2023 (DoS, 2023)—refugee influxes, and transboundary water constraints. Agriculture consumes more than half of Jordan's total water resources, placing increasing pressure on the sector to maintain productivity while reducing FW withdrawals. Although modernization of municipal systems and restructuring agricultural production could substantially reduce national water demand (Beithou et al., 2022), implementation remains limited, intensifying reliance on alternative water sources.

Within this context, the Jordan Valley (JV) has become the focal point of TWW reuse in agriculture. FW is increasingly blended with effluent from the As-Samra wastewater treatment plant to meet irrigation requirements (MWI, 2023). Tomatoes represent a cornerstone of this system due to their high economic value, short growth cycle, and strong domestic and export demand. They account for approximately 35.1% of Jordan's total crop production and contribute substantially to national vegetable consumption (Qtaishat et al., 2022; DoS, 2023). Despite their importance, tomato production in Jordan faces persistent constraints related to water scarcity, rising input costs, market volatility, and irrigation water quality, leading to pronounced interannual variability in yield and self-sufficiency (Alha mmad & Awaideh, 2023; Assaf et al., 2025; Qadir et al., 2025).

Traditionally, irrigation water suitability has been assessed primarily by using bulk salinity indicators, particularly electrical conductivity (EC). Tomatoes are generally classified as moderately salt-tolerant, with acceptable yield performance reported at EC levels of 1.5–2.5dS m^{-1} (Gabr, 2021). Jordan's blended TWW typically falls within this range (≤ 2.5dS m^{-1}; Jiries et al., 2010), suggesting apparent suitability based on conventional criteria. However, Jordan's distinct water chemistry, characterized by elevated sodium adsorption ratios and increasing concentrations of specific ions, may pose risks not captured by EC alone (Gharaibeh et al., 2024).

Recent evidence indicates that crop responses, particularly in tomato, are often governed by the accumulation of specific ions rather than overall salinity alone. Chloride (Cl^-), historically regarded mainly as a toxic salinity component, has emerged as a critical determinant of plant physiological performance under saline and water-limited conditions. Experimental and review studies demonstrate that excessive chloride accumulation disrupts osmotic balance, interferes with nutrient uptake, and impairs photosynthetic efficiency in tomato, resulting in reduced biomass, fruit set, and yield stability (Roșca et al., 2023; Yılmaz, 2026). Importantly, these adverse effects have been observed even when EC remains within conventionally acceptable limits, challenging the adequacy of EC-based irrigation thresholds (Khalid & Ashraf, 2025).

Physiological investigations further show that chloride toxicity affects membrane stability, chlorophyll content, nitrate reductase activity, and antioxidant balance, ultimately compromising tomato productivity and fruit quality (Roșca et al., 2023; Yılmaz, 2026). At the same time, controlled nutrition studies reveal that chloride can exert beneficial effects at low concentrations, enhancing stomatal regulation, water-use efficiency, and drought tolerance in tomato (Lucas Gutiérrez et al., 2024). This dual role underscores the importance of distinguishing chloride as a micronutrient and chloride accumulation resulting from prolonged irrigation with saline or reused water.

Management-oriented studies confirm that mitigating chloride accumulation, rather than reducing EC alone, can substantially improve tomato performance. Field and greenhouse experiments demonstrated that strategies such as halophyte-based phytodesalinization and organic amendments reduced chloride availability, improved nutrient homeostasis, and increased tomato yields by up to 27% under moderately saline conditions (Mughees Ud Din et al., 2023; Jurado et al., 2024). Global syntheses further highlight chloride-driven salinity stress as a dominant constraint in irrigated agriculture, particularly in arid and semi-arid regions where wastewater reuse is expanding (Derbew et al., 2026; Anarah et al., 2025).

Despite these advances, most irrigation guidelines and policy frameworks, especially in water-scarce countries, continue to rely primarily on EC thresholds, overlooking chloride-specific risks. This gap is particularly relevant in blended TWW systems, where EC may remain stable while chloride concentrations progressively increase. In Jordan, preliminary evidence indicates that tomatoes retain relatively high self-sufficiency (85–90%) under blended TWW irrigation, outperforming cereals such as wheat, which experience substantial productivity declines under similar conditions (AlBtoosh et al., 2024). While this resilience highlights tomato's strategic importance, it also raises concerns regarding long-term sustainability if chloride accumulation is not explicitly addressed.

Jordan's National Water Strategy (2023–2040) promotes expanded TWW reuse but lacks crop-specific irrigation guidelines that account for localized interactions between water quality and yield (MWI, 2023). Similarly, the National Food Security Strategy prioritizes increasing domestic production but does not provide tomato-specific irrigation standards, despite tomatoes supplying nearly

15% of national vegetable consumption and playing a key role in food self-sufficiency (FAO, 2020; DoS, 2022). This policy gap limits evidence-based decision-making and constrains the development of targeted, water-efficient strategies for high-value crops.

Against this backdrop, there is a clear need for long-term, data-driven evaluation of tomato production under blended wastewater (BW) irrigation that jointly considers water quantity, water quality, and food security outcomes. In particular, the relative importance of chloride concentration compared with bulk salinity remains underexplored in arid agricultural systems. Accordingly, this study investigates the relationships between irrigation water quantity, irrigation water quality, and tomato self-sufficiency in Jordan's JV over the period 2008–2023. Using stepwise regression supported by stationarity diagnostics, the study evaluates how FW and BW availability, together with key water quality parameters, including EC and chloride, influence tomato productivity and self-sufficiency. The central hypothesis is that tomato self-sufficiency is more sensitive to chloride accumulation than to overall salinity, and that crop water requirements alone cannot explain observed variability in food security outcomes. By explicitly distinguishing chloride effects from bulk salinity, this research provides novel insights to support crop-specific irrigation standards and sustainable water–food security planning in arid regions.

MATERIALS & METHODS

Study Area Description

The North and Middle JV (32°31.5'N; 35°35.5'E) constitutes Jordan's principal agricultural region and is one of the country's most productive areas for both local consumption and export crops, as shown in Fig. 1. This region serves as the heart of vegetable cultivation, particularly tomatoes, which are among Jordan's most important horticultural co mmodities. The area is characterized by a Mediterranean climate, with long, hot su mmers where temperatures frequently exceed 40°C, and mild winters ranging from 10°C to 20°C. Rainfall in the JV exhibits a north-to-south gradient, with annual precipitation levels ranging from approximately 500 mm in the northern sections to as little as 200 mm in the southern parts (Rodrigo-Comino et al., 2021).

The climatic conditions, combined with fertile alluvial soils derived from river and wadi deposits, create a favorable environment for intensive year-round agriculture. The region's soils are generally rich in nutrients and have good water-holding capacity, enabling the cultivation of a wide range of crops under both open-field and protected greenhouse systems. The North and Middle JV are particularly noted to produce high-value crops such as tomatoes, cucumbers, peppers, and leafy vegetables, alongside fruit crops including dates, citrus, and bananas (Ananda et al., 2020; Anbar et al., 2020).

In addition to natural advantages, the area benefits from an extensive irrigation infrastructure supplied by the King Abdullah Canal and groundwater wells, which ensure a relatively stable water supply throughout the year Al-Kharabsheh (2020). This has allowed farmers to adopt modern agricultural practices and extend production seasons to meet both domestic and export market demands. However, the region also faces environmental and resource challenges, including increasing water scarcity, soil salinization, and the impacts of rising temperatures, which pose potential threats to long-term agricultural sustainability.

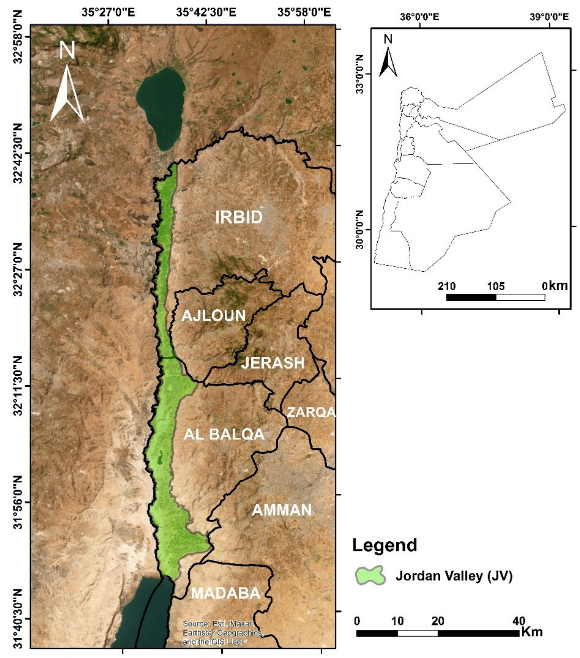

Fig. 1: Location of the North and Middle JV within Jordan (32°31.5'N, 35°35.5'E), showing the geographic extent of the study area analyzed in this research.

Although the Jordan River, springs, and groundwater are the main sources of irrigation water, there is still a shortage because of increased demand and climate change. Increasingly, TWW is being combined with King Talal Dam water (MWI, 2023) and used for irrigation, especially in the middle JV (Almanaseer et al., 2020; Tawfik et al., 2023).

Stationarity and Regression Modelling

The Augmented Dickey–Fuller (ADF) test was applied to all indicators for the period 2008–2023 to assess the stationarity of the time-series variables prior to regression modelling, the test evaluates the presence of a unit root by estimating the null hypothesis that each series is non-stationary in levels. For each variable, the ADF statistics, associated *p*-value, and critical values at the 1%, 5%, and 10% significance levels were computed. Optimal lag lengths were automatically selected based on the Akaike Information Criterion (AIC) to control serial correlation in the residuals. Variables that were stationary in levels were retained in their original form, whereas non-stationary series were identified for potential transformation prior to inclusion in regression analysis. This procedure ensures that the statistical properties of the data are appropriate for time-series modeling and reduces the risk of spurious regression relationships (Ivanovski & Ivanovska, 2024). The Augmented Dickey-Fuller (ADF) test was employed to verify the stationarity of the time-series data as shown in Equation (1):

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \epsilon_t \quad (1)$$

where y_t is the time-series variable, $\Delta y_t = y_t - y_{t-1}$ is the first difference, α is a constant (drift term), βt is the deterministic time trend (optional depending on model), γ is the coefficient tested for stationarity (key parameter), p is the number of lagged difference terms, δ_i is the coefficient of lagged difference, and ϵ_t is the white-noise error term.

Stepwise regression analysis was applied to identify the most influential explanatory variables governing tomato yield and self-sufficiency under conditions of water scarcity. The method was selected to support exploratory variable screening in a multi-indicator framework, where climatic, water-quality, and water-availability variables are interrelated. The underlying assumptions of the regression framework include linear relationships between predictors and the response variable, independence of residuals, homoscedasticity, and the absence of strong multicollinearity among explanatory variables.

A forward selection procedure was adopted, whereby candidate variables were sequentially included only when they produced statistically significant improvements in model performance, as measured by *p*-values and changes in the adjusted coefficient of determination (Adjusted R^2). Prior to model estimation, pairwise correlation analysis was conducted to assess multicollinearity, ensuring that highly correlated variables were not simultaneously retained in the model. This approach supports the development of a parsimonious regression structure while reducing redundancy among predictors.

While stepwise regression has recognized limitations, such as sensitivity to sample size, potential instability in variable selection, and the risk of excluding variables with indirect effects (Ansarifar et al., 2021), it remains widely applied in agro-hydrological and crop–water studies for identifying dominant drivers where the primary objective is interpretability rather than prediction alone (Zhang & Li, 2023). In this study, stepwise regression was therefore used as a diagnostic and screening tool to highlight key dependencies between tomato production, water scarcity, and water quality indicators, rather than as a definitive causal model.

To ensure the validity of the time-series regression, stationarity was evaluated prior to model estimation. Variables that satisfied stationarity conditions in levels were retained in their original form, while non-stationary series were appropriately treated before inclusion in the regression framework. This pre-processing step minimized the risk of spurious relationships and ensured consistency between the statistical assumptions and the applied modeling approach.

The general form of the multiple regression model used in this study is expressed in Equation (2):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon \quad (2)$$

where Y represents the dependent variable (tomato yield), β_0 is the intercept, β_i are the regression coefficients corresponding to the independent variables X_i, and ε denotes the random error term.

Water Scarcity and Food Security Indicators

Data on water scarcity and food security indicators (2008–2023) were obtained from Jordan's Department of Statistics (DOS), Ministry of Agriculture (MOA), Ministry of Water and Irrigation (MWI), and the Jordan Valley Authority (JVA). Seasonal decomposition was applied to the time-series data to examine trend, seasonal patterns, and residual components (Rogachev & Simonov, 2022; Gordan et al., 2024; Bandara et al., 2025). The crop water requirement (CWR) for tomatoes was estimated using FAO's CROPWAT 8.0 software (Allen, 2002), with reference evapotranspiration (ETo) calculated from local climate records (Al-Baqura and Dier Allah stations) and crop coefficients (Kc) specific to tomatoes, ranging from 0.6 to 1.2.

Key indicators for assessing water scarcity and food security in Jordan (Table 1) encompass agricultural and water-related factors. Agricultural indicators include tomato cultivation area, production under FW and BW irrigation and production yield (Heiba et al., 2023; Martínez-Valderrama et al., 2023). Water quantity and quality metrics cover irrigation volumes (Alkhaza'leh et al., 2023), crop water requirements estimated via CROPWAT 8.0 and CLIMWAT (Doorenbos et al., 1980; Allen et al., 2002), and salinity and chloride levels (Abuzaid & Jahin, 2021). Together, these indicators provide a comprehensive framework to evaluate trade-offs between water availability and food production, supporting sustainable irrigation and water management strategies.

Table 1: Key indicators for assessing water scarcity and food security in Jordan

Category	Indicators	Code	Unit	Source
Agricultural	Tomato cultivated area irrigated with FW at JV	ATFWJV	Dunum (du)	MoA, JVA
	Tomato cultivated area irrigated with BW at JV	ATBWJV	Dunum (du)	MoA, JVA
	Tomato yield production in Jordan	TPRJOR	ton/du	DoS
	Jordan Self-sufficiency of tomato	SSTJOR	%	MoA, JVA
Water Quantity	Effective rainfall at areas irrigated with BW at JV	ERBWJV	mm	MWI
	FW irrigation supply at JV	QWSTFWJV	m^3/du	MWI
	BW irrigation supply at JV	QWSTBWJV	m^3/du	MWI
	Crop water requirement (CWR) for FW at JV	CWRTFWJV	mm	CROPWAT 8.0
Water Quality	Salinity (EC) of BW at JV	ECBWJV	dS/m	MWI
	Chloride (Cl) of BW at JV	CLBWJV	ppm	MWI

RESULTS

Self-sufficiency Trends with Water Scarcity and Food Security Indicators

The relationship between effective rainfall and tomato self-sufficiency from 2008 to 2023 is shown in Fig. 2. Although effective rainfall displayed a downward trend during this period, tomato self-sufficiency values remained highly variable, fluctuating between 146.1% and 337.4%. This divergence suggests that while rainfall is a contributing factor, it does not serve as the predominant determinant of self-sufficiency. Rather, the wide variability in self-sufficiency likely reflects the influence of other critical factors, such as production strategies, market dynamics, and agronomic practices, and underscores the complex nature of achieving food security under water scarcity (Su et al., 2024; Zeng et al., 2025; Dzvene et al., 2025).

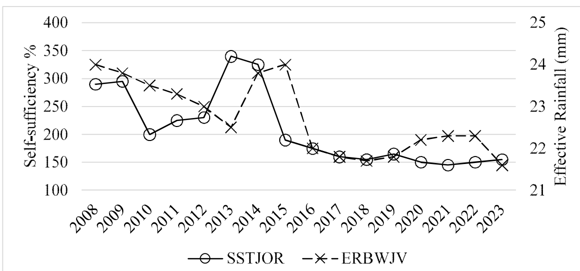

Fig. 2: Temporal variation in effective rainfall (mm) and tomato self-sufficiency (%) in the JV from 2008 to 2023, illustrating interannual rainfall decline alongside pronounced variability in tomato self-sufficiency.

In contrast, the crop water requirement for tomato irrigated with FW remained relatively consistent, between 418 mm and 420 mm, as shown in Fig. 3. This stability in water demand, coupled with pronounced fluctuations in self-sufficiency, suggests that factors beyond water availability, such as market dynamics, agronomic practices, and potential shifts in cultivation areas, play a more substantial role in influencing self-sufficiency levels (Soltani et al., 2024; Mamassi et al., 2025).

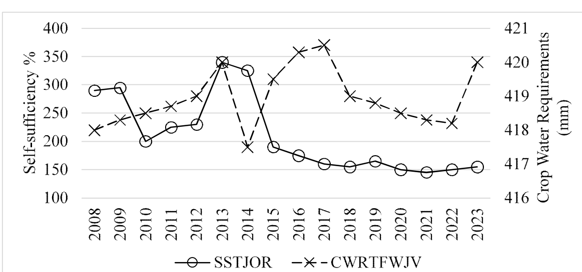

Fig. 3: Annual crop water requirements for tomato under FW irrigation (mm) and corresponding tomato self-sufficiency (%) in the JV during the period 2008–2023.

The FW EC declines progressively from 320–330 ($\times10^{-2}$dS/m) in 2008–2010 to 210$\times10^{-2}$dS/m in 2020, before increasing again toward 270$\times10^{-2}$dS/m by 2023, as shown in Fig. 4. This pattern suggests a long-term improvement in FW quality until 2020, followed by a partial reversal. In contrast, the salinity of BW remains relatively stable (140–155 $\times10^{-2}$dS/m), aside from a minimum in 2013–2014 (130–140 $\times10^{-2}$dS/m), indicating consistent tertiary-level water quality despite changes in supply sources (Ntanasi et al., 2024).

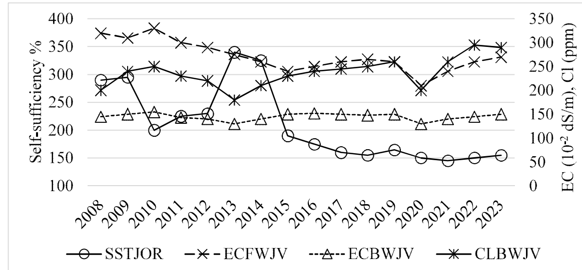

Fig. 4: Temporal variation in EC of FW (ECFW; $\times10^{-2}$dS m^{-1}) and BW (ECBW; $\times10^{-2}$dS m^{-1}) used for tomato irrigation in the JV from 2008 to 2023.

Chloride levels in BW show a clear upward trend, increasing from 200 ppm in 2008 to nearly 300 ppm by 2022. These signals increase salinity stress risk, particularly in later years, and align with regional reports of rising salt accumulation in reused irrigation water (Alqardaeai et al., 2025).

A visual comparison indicates that the highest self-sufficiency years (2013–2014) coincide with lowest salinity levels in both FW (275–260) and BW (130–140), and with lowest chloride concentrations (180–210 ppm). Conversely, years with reduced self-sufficiency (2018–2023) correspond to elevated chloride levels (>250 ppm) and a rebound in the FW EC, suggesting that worsening water quality has increasingly constrained tomato productivity as claimed by Chand et al. (2020).

Overall, the data suggests a negative association between tomato self-sufficiency and salinity indicators, particularly chloride concentrations, supporting the hypothesis that water quality deterioration is a contributing factor to declining national tomato supply security. The stability of ECBWJV alongside rising CLBWJV further indicates that chloride, rather than overall EC, is emerging as the more limiting factor. These findings align with previous studies demonstrating the heightened sensitivity of tomato yield and market stability to chloride-driven salinity stress in irrigated systems (Conti et al., 2023; Roșca et al., 2023; Tola et al., 2023; Zhang et al., 2025).

The observed negative association between tomato self-sufficiency and chloride concentration can be explained by well-documented physiological and agronomic responses of tomato plants to chloride stress. Excessive chloride uptake disrupts ionic balance, interferes with nitrate assimilation, and reduces photosynthetic efficiency through chlorophyll degradation and impaired photosystem II activity, ultimately constraining biomass accumulation and fruit development (Roșca et al., 2023; Yılmaz, 2026). Unlike bulk salinity expressed as EC, which reflects total dissolved salts, chloride exerts a more direct toxic effect at the cellular level, affecting membrane stability and enzyme activity even when EC remains within agronomically acceptable thresholds. This distinction explains why ECBWJV remained relatively stable while rising CLBWJV coincided with declining self-sufficiency in later years.

At the agronomic scale, prolonged exposure to chloride-rich irrigation water can reduce nutrient use efficiency and exacerbate oxidative stress, increasing crop sensitivity to additional stressors such as heat and water deficits (Roșca et al., 2023). Conversely, controlled chloride supply at low concentrations may enhance water-use efficiency and stomatal regulation, particularly under drought conditions, highlighting the dual role of chloride as both a beneficial nutrient and a limiting stress factor depending on its concentration and duration of exposure (Lucas Gutiérrez et al., 2024). Field and greenhouse studies further demonstrate that mitigating chloride accumulation, rather than reducing EC alone, can significantly improve tomato physiological performance and yield stability under saline irrigation (Mughees Ud Din et al., 2023; Jurado et al., 2024). These findings support the interpretation that chloride accumulation is a key driver of the long-term constraints observed in tomato self-sufficiency under BW irrigation.

Descriptive Statistical Analysis of Parameters

Table 2 provides a comprehensive overview of key indicators for tomato cultivation across the Middle JV, North JV, and the wider Jordan region. It su mmarizes agricultural and water quantity and quality metrics, offering detailed insights into crop production, irrigation practices, and environmental conditions affecting tomato farming, in addition to tomato production and self-sufficiency indicators at the national level (Alshami et al., 2023; Tian et al., 2024; Alghamdi et al., 2024; Obadi et al., 2024).

Table 2: Key indicators for assessing water scarcity and food security in Jordan

Indicator	Unit	Statistics				
		Maximum	Minimum	Mean	Standard deviation	Coefficient of variation
ATFWJV	du	9049.9	3940	6302	1452	0.23
ATBWJV	du	24926.6	8000	13601	3709	0.27
QWSTFWJV	m^3/du	724.9	381.4	569.7	90.9	0.16
QWSTBWJV	m^3/du	362.1	166	283	53	0.19
CWRTFWJV	mm	420.1	418	419	1	0.00
TPJOR	ton	870017	556544	705671	97901	0.14
SSTJOR	%	337.4	146.1	210.5	64.7	0.31

Based on the statistics calculated for Table 2, the area indicators (ATFWJV, ATBWJV) illustrate the spatial scale of tomato cultivation across different irrigation categories. The FW and BW sub-categories (ATFWJV and ATBWJV) encompass smaller areas; notably, ATBWJV displays the greatest variability (coefficient of variation = 0.27), suggesting that cultivation using BW is less consistent than that under FW. The tomato production indicator further reveals substantial disparities in total tomato output. TPRJOR displayed the lowest variability (coefficient of variation = 0.14), indicating relatively stable efficiency at the national level. Regarding water supply metrics, QWSTFWJV (mean = 569.7m³/du) exceeds QWSTBWJV (mean = 283m³/du), with coefficients of variation of 0.16 and 0.19, respectively, implying moderate variation in water delivery across the two systems. Lastly, the crop water requirement indicators (CWRTFWJV: mean = 419 mm; CWRTBWJV: mean = 409 mm) show virtually no variation (coefficient of variation = 0.00), which underscores the predictability and stability of tomato water requirements across locations in the JV. This observation is consistent with the findings reported by Somefun et al. (2024).

Tomato production in Jordan ranges from 556,544 tons to 870,017 tons, with a mean of 705,671 tons. The standard deviation of 97,901 tons and a coefficient of variation of 0.14 indicate relatively low variability in production levels. Tomato self-sufficiency remains high, ranging from 146.1% to 337.4% and averaging 210.5%. However, the standard deviation of 64.7% and a coefficient variation of 0.31 suggest notable fluctuations in self-sufficiency, likely driven by variations in production and domestic consumption patterns. These findings are consistent with recent studies demonstrating that crop output and self-sufficiency in arid regions are sensitive to irrigation management and environmental conditions (Kanzari et al., 2024; Bian et al., 2024; Yang et al., 2025; Khawar et al., 2025).

The comparatively high resilience of tomato self-sufficiency relative to cereal crops under BW irrigation reflects both physiological and agronomic advantages. Tomatoes exhibit moderate salt tolerance and possess a greater capacity for osmotic adjustment, enabling them to maintain turgor and metabolic activity under elevated salinity and chloride conditions (Roșca et al., 2023). In contrast, cereal crops such as wheat are more sensitive to ionic stress, particularly during early growth and grain filling stages, leading to sharper productivity declines under similar irrigation regimes. Tomato's relatively short growth cycle and flexible planting schedules further allow producers to adopt cultivation practices in response to water availability and quality constraints, buffering production against short-term environmental variability.

In addition, tomato production systems are often supported by higher input intensity, targeted management practices, and stronger market incentives compared with staple cereals, which enhances the crop's capacity to sustain yields under marginal water quality conditions. Physiological evidence indicates that tomato plants can partially compartmentalize chloride ions within vacuoles, reducing cytoplasmic toxicity and preserving photosynthetic function, a mechanism less effective in many cereal species (Lucas Gutiérrez et al., 2024). These combined traits help explain why tomatoes maintained high self-sufficiency levels under BW irrigation, while cereals experienced more pronounced declines, reinforcing tomato's strategic role in food security under water-scarce conditions.

Stationarity Assessment of Parameters

To evaluate the temporal behavior and suitability of the key variables for regression modelling, the ADF test was applied to all time-series indicators for the period 2008–2023. The results reveal a mixed pattern of stationarity across the dataset, indicating that tomato-related agricultural and water-quality variables exhibit distinct long-term dynamics, as shown in (Table 3).

Table 3: Su mmary of the Augmented Dickey–Fuller tests on each series

Series	ADF stat	*p*-value	Lags	N obs	Stationary at 5%? *
SSTJOR	-8.75	2.8×10^{-14}	6	9	Yes
ERBWJV	-0.39	0.910	6	9	No
CWRTFWJV	-0.96	0.770	5	10	No
ECBWJV	-2.77	0.063	5	10	Borderline (No at 5%, Yes at 10%)
CLBWJV	2.49	0.999	6	9	No

*Decision based on *p*-value < 0.05 and comparison with critical values.

The self-sufficiency series (SSTJOR) exhibits a strongly negative ADF statistic (–8.75) with a highly significant *p*-value ($<10^{-13}$), confirming its stationarity in levels. This indicates stable long-run fluctuations with no persistent trend, consistent with the cyclical nature of national tomato market supply and annual production variability.

In contrast, several other indicators do not meet the 5% significance threshold. Effective rainfall under BW conditions (ERBWJV) and crop water requirements under FW (CWRTFWJV) both show high *p*-values (>0.75), indicating non-stationary behavior. These variables appear to follow slow-moving or trend-like patterns, likely driven by climatic variability and evolving agricultural water-management practices. Chloride concentration in BW (CLBWJV) is also non-stationary (ADF = 2.49; $p \approx 1.0$), reflecting substantial interannual variability associated with changes in upstream wastewater sources and treatment performance.

The EC of BW falls near the threshold (ADF = –2.77; p = 0.063), suggesting borderline stationarity, non-stationary at the 5% level but stationary at the 10% level. This intermediate behavior may correspond to gradual shifts in wastewater composition over time rather than abrupt year-to-year changes.

Overall, these results confirm that some variables, particularly SSTJOR and ECFWJV, are suitable for direct inclusion in regression models in their level form, while others may require differencing or trend-adjusted formulations. The presence of non-stationarity in climatic and wastewater-quality parameters highlights the influence of long-term environmental change and infrastructure evolution on tomato production systems in the JV.

Dependency on Water Scarcity and Food Security Indicators

Stepwise regression was employed to model crop production, with predictor variables selected automatically based on R-squared, adjusted R-squared, and *p*-value criteria. Crop production served as the dependent variable (Y), while agricultural and water quantity and quality indicators were the independent variables (X). Following the general multiple regression form (Stock & Watson, 2019), the model is expressed as:

$$\text{Crop Production} = \beta_0 + \beta_1(\text{Area indicators}) + \beta_2(\text{Production indicators}) + \beta_3(\text{Water supply indicators}) + \beta_4(\text{Crop water requirement indicators}) \quad (4)$$

The ANOVA table (Table 4) for tomato crops presents each variable's parameter estimate, standard error, Type II sum of squares (SS), F-value, and *p*-value (Pr > F). No additional variables met the 0.1500 significance level for inclusion. The following section presents the fitted model and interprets the results.

Table 4: Analysis of variance for Tomato

Variable	Parameter Estimate	Standard Error	Type II SS	F Value	Pr > F
Intercept	-407350	497082	4277697969	0.67	0.4273
CWRTFWJV	-294458	64156	4413446077	15.0	0.0031
ERBWJV	67132	23013	54203304774	8.51	0.0120
ECBWJV	-219244	86713	40720905394	6.39	0.0252

Equation 3 su mmarizes the stepwise regression results linking tomato production in Jordan to key water scarcity and food security indicators:

$$\text{TPJOR} = -407{,}350 - 294{,}458 \times \text{CWRTFWJV} + 67{,}132 \times \text{ERBWJV} - 219{,}244 \times \text{ECBWJV}$$

The ERBWJV positively influences tomato yield, with a parameter estimate of 67,132 and an F-value of 8.51 (Pr > F = 0.012), suggesting that rainfall can partially alleviate water stress (Sha mmout et al., 2023). Crop water requirements (CWRTFWJV) are critical for growth, showing a negative estimate of –294,458 (F = 15, Pr > F = 0.0031), highlighting the importance of adequate irrigation (Hamaideh et al., 2024). Water quality (ECBWJV) also significantly affects production, with a negative estimate of –219,244 (F = 6.39, Pr > F = 0.0252), indicating that poor water quality reduces tomato yield (Whetton et al., 2021; Wang et al., 2023; Shewangizaw et al., 2024).

Recent methodological assessments warn that automated procedures such as stepwise regression may produce unstable variable selection and biased inference, particularly under multicollinearity and limited sample sizes (Wdowicka, 2023). Nonetheless, AlBtoosh et al. (2024) demonstrated that stepwise regression remains a powerful tool for identifying crop–water dependency relationships.

From a policy and management perspective, these findings highlight the limitations of irrigation guidelines that rely solely on bulk salinity indicators such as EC. In arid and semi-arid regions where TWW reuse is expanding, chloride concentrations may increase progressively even when EC remains stable, posing hidden long-term risks to crop productivity. The results suggest that irrigation standards should incorporate chloride-specific thresholds, particularly for high-value and widely cultivated crops such as tomato, to avoid gradual yield erosion and instability in food supply.

For Jordan and similar water-scarce regions, integrating chloride monitoring into wastewater blending strategies and irrigation scheduling could improve water-use efficiency while safeguarding crop performance. Practical measures, including optimized blending ratios, periodic leaching practices, and soil amendments, have been shown to mitigate chloride accumulation and enhance tomato productivity under saline irrigation (Mughees Ud Din et al., 2023; Jurado et al., 2024). More broadly, adopting crop-specific, ion-focused water quality management frameworks can support sustainable wastewater reuse, enhance agricultural resilience, and improve food security outcomes across arid and semi-arid agroecosystems (Derbew et al., 2026).

Conclusions

This study assessed the interactions between water scarcity, irrigation water quality, and tomato self-sufficiency in Jordan over the period 2008–2023. Tomato production remained relatively stable, ranging from approximately 556,000 tons to 870,000 tons, while self-sufficiency levels were consistently high (146–337%, mean = 210.5%). Crop water requirements showed virtually no variation across FW and BW systems (~419 mm and ~409 mm, respectively), confirming the predictability of tomato water demand. These findings demonstrate that tomato self-sufficiency is only partially driven by water quantity, with broader influences from management practices, cultivated area, and market dynamics.

Water quality analysis revealed a clear and increasingly important constraint. Chloride concentrations in BW rose steadily from ~200 ppm in 2008 to nearly 300 ppm by 2022, while overall EC remained comparatively stable. Years of highest self-sufficiency (2013–2014) coincided with the lowest salinity and chloride levels in both FW and blended water, whereas periods of reduced self-sufficiency (2018–2023) corresponded to chloride concentrations exceeding 250 ppm. This pattern indicates that chloride accumulation, rather than bulk salinity, is emerging as the dominant limiting factor for tomato productivity under wastewater irrigation. Stationarity analysis further confirmed that tomato self-sufficiency remains structurally stable over time, while water quality indicators exhibit trend-driven variability, underscoring the need for salinity- and ion-specific management.

From a policy perspective, these results support a shift away from uniform irrigation regulations toward crop-specific water quality thresholds, particularly for strategically important and relatively resilient crops such as tomato. Strengthening chloride monitoring in TWW, optimizing blending ratios, and supporting farmer-level adaptation measures can help sustain high self-sufficiency while reducing pressure on scarce FW resources. Collectively, the findings contribute to SDG 2 (Zero Hunger) by reinforcing domestic food supply, SDG 6 (Clean Water and Sanitation) through safer and more efficient wastewater reuse, and SDG 12 (Responsible Consumption and Production) by promoting resource-efficient irrigation practices. Addressing chloride-driven salinity risks will be critical for ensuring a water-secure and food-secure agricultural future in Jordan.

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