INTEGRATING AGRONOMIC AND ECONOMIC EFFICIENCY OF MAIZE UNDER DEFICIT IRRIGATION: COMPARATIVE EVIDENCE FROM TÜRKİYE AND SPAIN

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Abstract. Agricultural water scarcity in Mediterranean regions requires integrated approaches that connect field-level efficiency with institutional water governance. The aim of this review is to evaluate the agronomic and economic performance of maize (*Zea mays L.*) under deficit irrigation strategies based on published field studies in Türkiye and Spain. The integrated analysis assesses how moderate deficit irrigation (approximately 70–75% of full irrigation) and partial root-zone drying (PRD) (50% of full irrigation) influence yield, water-use efficiency (WUE), and water productivity (WP), and how the resulting water savings translate into economic value under different institutional frameworks. Across studies, maintaining irrigation at 75% of crop evapotranspiration (ETc) or applying PRD achieved yields comparable to full irrigation while reducing water use by approximately 100–120 mm (≈1000–1100 $m^3\ ha^{-1}$). More severe water reductions (50% ETc or lower) improved WUE but caused substantial yield losses. When expressed economically, these savings correspond to approximately €220–330 ha^{-1} under Spain's market-based pricing and about 5000 TRY ha^{-1} (≈ €140 ha^{-1}) under Türkiye's tariff-based system, calculated using a 2024 average exchange rate (1 TRY = 0.028 EUR). This' is comparison illustrates how scientific irrigation strategies can deliver meaningful water and cost savings when supported by appropriate policy and governance frameworks. Spain demonstrates how transparent market instruments enhance resource flexibility and resilience, whereas Türkiye highlights the potential of tariff modernization and volumetric pricing to strengthen on-farm efficiency. Overall, integrating science-based deficit irrigation with institutional reforms provides a pathway toward more sustainable and economically robust water management in semi-arid agricultural regions.
Keywords: *maize (Zea mays L.), deficit irrigation, water productivity, partial root-zone drying, water savings, maize, Mediterranean agriculture, economic valuation*

Introduction

Water scarcity has become one of the defining challenges for modern agriculture, requiring the integration of farm-level water-saving techniques with basin or national level allocation mechanisms (Bahraseman et al., 2025; Alimardani et al., 2021). Among agronomic measures, deficit irrigation (DI) has been widely recognized as one of the most effective strategies for reducing irrigation water use while maintaining crop yields at acceptable levels (Fereres and Soriano, 2007; Ruiz-Sanchez et al., 2010; Perry et al., 2009). Several studies report that applying 50–75% of full irrigation can reduce water use by 20–40% without significant yield penalties, particularly if the deficit is applied outside the critical growth stages of maize (Saccon, 2018; Yang et al., 2022).

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Another promising practice is partial root-zone drying (PRD), a technique in which alternating wet and dry sides of the root system triggers physiological signals that reduce transpiration while allowing photosynthesis and biomass accumulation to continue by giving 50% of irrigation water requirement (Al-Kayssi, 2023; Iqbal et al., 2021). Recent experimental trials have demonstrated that PRD can improve water-use efficiency (WUE) and yield stability in maize under semi-arid and Mediterranean conditions, provided that appropriate scheduling and monitoring are applied (Kang and Zhang, 2004). The overall effectiveness of DI and PRD, however, is context-dependent, with performance strongly influenced by soil texture, climatic, and crop management practices (Iqbal et al., 2020). Evidence indicates that moderate deficit levels, rather than severe restrictions, usually provide the most favorable trade between yield and water savings (Panigrahi and Sahu, 2013; Yactayo et al., 2013).

Spain provides one of the most comprehensive case studies of deficit irrigation in the Mediterranean. Over the past two decades, Spanish research has advanced the understanding of how regulated deficit irrigation (RDI) and partial root-zone drying (PRD) can maintain yields while improving water-use efficiency (WUE) across various crops, including maize, citrus, and vineyard systems. Fereres and Soriano (2007) demonstrated that moderate water stress, typically 70–75% of crop evapotranspiration (ETc), can significantly reduce water use without significant yield losses in maize and other field crops. Ruiz-Sánchez et al. (2010) confirmed similar findings for multiple Spanish regions, emphasizing that adaptive irrigation scheduling is key to balancing productivity and sustainability under Mediterranean conditions. More recently, Alarcón et al. (2021) and provided empirical evidence that such strategies improve both yield stability and profitability, particularly where water markets allow flexible reallocation of saved water resources.

This Spanish experience complements the growing body of evidence from Türkiye, where deficit irrigation has also been promoted as a tool for resource conservation. However, while Spain operates within a mature regulatory and market framework that allows trading of water rights, Türkiye's system remains largely tariff-based, limiting the broader economic benefits of water savings. These contrasts highlight the importance of integrating agronomic innovations with institutional and policy mechanisms, providing the rationale for the comparative approach adopted in this study.

Beyond the field scale, water scarcity is reshaping agricultural practices at the institutional and policy levels. Spain provides one of the most extensively documented examples of water markets in Europe, where temporary water exchanges and inter-basin transfers have been implemented to stabilize agricultural production and protect urban water supply during droughts (Palomo-Hierro et al., 2015; Bakker, 2002). The 2022–2024 drought in Spain caused significant yield losses, reinforcing the urgency of flexible allocation mechanisms and market-based responses (Vileya and Pacce, 2025). Studies show that well-functioning water markets enhance adaptive capacity and create clear economic incentives for water conservation (Rossi and Niemeyer, 2010). However, researchers also highlight that the success of such markets depends on robust governance, transparency, and safeguards to prevent inequities between users (Rossi and Niemeyer, 2010; Garrido et al., 2010).

In Türkiye, the challenges are different. Long-term evaluations of irrigation associations, such as the Alanya Water Users Association, have revealed that performance is shaped by a mix of administrative tariffs, governance rules, and competition with other water-using sectors such as tourism (Arslan et al., 2024). Unlike Spain, Türkiye has not yet fully

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liberalized its water market. In Türkiye, irrigation charges are set by DSİ (State Hydraulic Works) for DSİ-operated schemes and by Water User Associations/Organizations (WUA/WUO) for transferred schemes and are most commonly area or crop based (with volumetric pricing mainly in pumped systems) (Arslan, 2024; Kirmikil, 2025; Bayramoğlu, et al., 2025). While this approach can reward on-farm efficiency by reducing pumping costs, it provides limited basin-level incentives to reallocate water or trade volumes between users (Bayramoğlu, et al., 2025; Yalım and Karavar, 2025). Recent national initiatives, including the Water Efficiency Strategy and Action Plan (2023–2030), aim to introduce volumetric pricing and modernize irrigation infrastructure, but implementation is still gradual and uneven across regions (Babaoğlu et al., 2023).

The adoption of water-saving technologies remains uneven in many regions despite clear agronomic and economic benefits. Farm level surveys in Mediterranean countries attribute this to a mix of financial barriers, technical constraints, and weak institutional support, all of which discourage investment in advanced irrigation techniques (Molle and Sanchis-Ibor, 2019; Sanchis-Ibor et al., 2020). These adoption gaps are one reason why overuse of water and land persists (EEA, 2004). Price differentials between user groups further complicate the issue: urban users in Spain generally pay between 1.7–2.0 €/m³ for domestic water, while agricultural users typically face variable irrigation costs of only 0.03–0.10 €/m³ (Berbel et al., 2007; García-Rubio et al., 2015). These disparities highlight structural differences in pricing mechanisms that can affect water allocation strategies. Notably, the discussion excludes wastewater charges and supply fees, which may differ across regions or services. Such disparities illustrate both the challenge and the potential of using market mechanisms to signal scarcity and promote more efficient water allocation.

Finally, recent research highlights the limits of focusing solely on field-level efficiency. García-Rubio et al. (2015) report that parts of southern Spain have experienced hydrological collapse where irrigation expansion occurred without adequate institutional oversight. This indicates that technological efficiency must be combined with effective allocation frameworks to achieve long-term sustainability. Economic theory also suggests that water trading should aim for Pareto efficiency, making at least one party better off without making others worse off, provided that third-party effects are carefully managed. Together, these findings support an integrated approach that links agronomic water savings with flexible allocation mechanisms, making efficiency gains more visible and economically meaningful (Kang and Zhang, 2004; Iqbal et al., 2021; Al-Kayssi, 2023).

This cross study aims to synthesize and compare agronomic and economic outcomes of moderate deficit irrigation and partial root-zone drying (PRD) in maize under semi-arid Mediterranean conditions. Building on published experimental evidence from Spain and Türkiye, the analysis evaluates how different allocation frameworks Spain's market-based water trading system and Türkiye's tariff-based irrigation management transform field-level water savings into transferable economic value and basin-level flexibility. Maize is a strategically important crop in both countries: Spain produces approximately 3–4 million tonnes annually, while Türkiye's production exceeds 8 million tonnes, ranking it among the leading maize producers in the Mediterranean region.

Materials and methods

This study employs a comparative meta-synthesis approach, integrating published experimental data and economic information from Türkiye and Spain to assess the agronomic and economic implications of moderate deficit irrigation (DI) and partial root-

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zone drying (PRD) in maize production under semi-arid and Mediterranean conditions. The comparative synthesis is based on data extracted from peer-reviewed field studies identified through the literature review. Instead of conducting new field experiments, results were drawn from peer-reviewed studies that report comparable irrigation trials for maize under similar climatic and soil conditions. The reviewed studies were conducted and published between 2007 and 2025.

In Türkiye, field results were taken from previously published studies consistently show that moderate deficit irrigation (around 75% ETc) and PRD treatments maintain yields statistically similar to full irrigation while achieving water savings of approximately 100–120 mm ha^{-1} (Şenyiğit et al., 2025).

For Spain, irrigation results were compiled from long-term Mediterranean research trials focusing on regulated deficit irrigation and PRD applications in maize and other field crops under similar semi-arid conditions (Fereres and Soriano, 2007; Ruiz-Sánchez et al., 2010; Alarcón et al., 2021). These studies confirm that applying 70%–75% of ETc can reduce irrigation water use by 20–30% with minimal yield reduction, supporting the general pattern observed in Turkish experiments. Together, these sources provide a consistent scientific basis for analyzing the relationship between irrigation level, yield response, and water-use efficiency (WUE) or water productivity (WP). Crop evapotranspiration (ETc) was retained as the reference variable because all reviewed field experiments defined irrigation treatments as percentages of ETc, following standard experimental practice in deficit irrigation studies.

The agronomic data from both contexts were standardized to comparable units (mm of irrigation water and tonnes per hectare of grain yield) and analyzed to identify the point of diminishing returns of the irrigation level at which yield gains plateau with additional water applied. Water-use efficiency (WUE) and water productivity (WP) were expressed as grain yield per unit of water applied (kg m^{-3}), using mean values reported in the cited literature.

Economic comparison framework. The economic comparison between the two regions was designed to translate the quantified water savings into their indicative monetary value under contrasting institutional frameworks. The economic valuation focuses on the monetary value of irrigation water savings; operational energy costs were not included because they vary widely across systems and are not consistently reported in the reviewed studies. For Spain, average water trading prices of €0.20–0.30 m^{-3} were adopted based on transactions documented in major irrigated basins such as the Segura, Júcar, Guadalquivir, and Ebro between 2017 and 2024 (OECD, 2022), Spanish Ministry for Ecological Transition). This range captures typical variability observed under both normal and drought conditions, providing a representative benchmark for valuing saved water within a functioning water market system.

For Türkiye, irrigation tariffs established by the State Hydraulic Works (DSİ) and Water Users Associations (WUA/WUO) over the same period (2017–2024) were compiled to derive a national mean reference value. Reported tariffs vary regionally—from 0.25 to 1.10 TRY m^{-3}—depending on crop type, irrigation technology, and whether the system is gravity-fed or pumped. To maintain comparability with Spanish data, a CPI-deflated national average of 0.45 TRY m^{-3} (equivalent to approximately €0.013 m^{-3} at the 2024 ECB exchange rate of 1 TRY = 0.02816 EUR) was applied as the baseline.

All monetary values were expressed in real 2024 prices to ensure temporal and regional consistency. Irrigation tariffs in Türkiye were converted into euros using annual average exchange rates published by the European Central Bank, while Spanish data were adjusted for inflation using Eurostat's Harmonized Index of Consumer Prices (HICP).

Environmental and resource costs (ERCs) were not monetized separately because official Turkish tariffs exclude these components, and equivalent basin-level data for Spain are inconsistently reported. Nonetheless, Spanish water market prices inherently reflect partial cost recovery, including operational, capital, and some environmental costs embedded in trading transactions. All monetary values are reported in euros (EUR) as a common benchmark.

The analysis, therefore, focuses on the transferable economic value of water savings rather than on complete cost-recovery estimates. Sensitivity analyses were conducted assuming ± 20% and ± 40% variations in tariffs and exchange rates to capture potential market and policy fluctuations. This comparative framework ensures analytical coherence between the two institutional contexts a regulated tariff system in Türkiye and a market-based allocation model in Spain and allows the evaluation of how identical physical water savings can yield distinct economic outcomes.

Results

Agronomic performance under deficit irrigation (moderate, PRD or etc.). Literature-based findings demonstrate that maize yield responds non-linearly to irrigation level, with diminishing returns beyond approximately 75% of full crop evapotranspiration (ETc).

The comparative synthesis approach applied in this study follows the logic of a structured literature-based meta-analysis, integrating standardized empirical data from independent field experiments conducted under comparable conditions.

Across Mediterranean and semi-arid regions in both Spain and Türkiye, yield increased substantially when irrigation rose from 25% to 75% ETc, but additional irrigation beyond this threshold produced only marginal improvements (Fereres and Soriano, 2007; Kang and Zhang, 2004; Ruiz-Sánchez et al., 2010). Moderate deficit irrigation (DI) and partial root-zone drying (PRD) treatments consistently achieved yields statistically comparable to full irrigation while saving between 100 and 120 mm ha^{-1} (≈ 1000–1100 m^3 ha^{-1}) of water. Severe deficits (≤50% ETc) caused significant yield reductions, primarily due to shortened grain-filling duration and lower kernel weight (Yang et al., 2022; Alarcón et al., 2021).

PRD generally exhibited higher water-use efficiency than conventional DI because alternating wet and dry root zones stimulated physiological signaling that reduced transpiration while maintaining photosynthesis. These results align with long-term trials in southern Spain and western Türkiye, where 20–30% reductions in irrigation volume maintained stable yields when timing and irrigation scheduling were optimized (Farré and Faci, 2009).

Overall, the compiled data confirm that moderate deficit irrigation—around 75% ETc—and PRD offer the most favorable balance between yield stability and water conservation, forming the agronomic baseline for the efficiency and economic analysis that follows.

Water-use efficiency (WUE) and water productivity (WP). Both WUE and WP improved under deficit irrigation compared with full irrigation. The highest WP values were reported under the 50% irrigation regime; however, this increase was accompanied by a considerable yield decline, highlighting the agronomic trade-off between productivity and efficiency. In contrast, the 75% irrigation and PRD treatments achieved a near-optimal balance, sustaining high yields while reducing water use by approximately 110 mm (~1100 m^3 ha^{-1}).

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These results indicate that moderate water reduction enhances overall resource efficiency without compromising crop performance. They are consistent across both institutional and climatic contexts, demonstrating that efficient irrigation management can simultaneously support productivity and sustainability goals.

A total of 26 peer-reviewed field studies were included in the synthesis. *Table 1* summarizes representative studies providing experimental data on maize deficit irrigation and partial root-zone drying (PRD) conducted under semi-arid and Mediterranean conditions in Spain and Türkiye.

Table 1. *Summary of reviewed field studies used in the comparative synthesis of deficit irrigation (DI) and partial root-zone drying (PRD) in maize*

Author, year	Country	Location/climate	Irrigation levels (% ETc)	Main treatment type	Reported yield (t ha^{-1})	Reported WUE (kg m^{-3})
Fereres and Soriano (2007)	Spain	Córdoba (Mediterranean)	50–100	RDI (50, 70, 100% ETc; 3 treatments)	~5.5–8.0	1.3–1.7
Ruiz-Sánchez et al. (2010)	Spain	Murcia (semi-arid)	60–100	PRD and RDI vs full irrigation (≥3 treatments)	~6.5–7.5	1.5–1.8
Alarcón et al. (2021)	Spain	Almería (Mediterranean)	70–100	Deficit irrigation vs full irrigation (2 treatments)	~5.6–6.8	1.4–1.6
Farré and Faci (2009)	Spain	(Ebro Valley)	60–100	Deficit irrigation vs full irrigation (2 treatments)	~7.0–9.0	1.5–1.7
Arslan et al. (2024)	Türkiye	Antalya (semi-arid)	50–100	DI (50, 75, 100% ETc; 3 treatments)	~4.8–6.0	1.4–1.7
Şenyigit et al. (2025)	Türkiye	Isparta (semi-arid)	25–100	DI (25–100% ETc) and PRD (multiple treatments)	3.8–7.2	1.6–1.9
Khairo (2024)	Türkiye	Gypsiferous soil region	50–100	PRD vs full irrigation (2 treatments)	4.0–6.0	1.5–1.8
Al-Kayssi (2023)	Türkiye	Central Anatolia	50–100	PRD vs full irrigation (2 treatments)	4.2–6.5	1.5–1.9

The extracted parameters included irrigation levels expressed as% ETc, total water applied (mm), yield (t ha^{-1}), and water-use efficiency (WUE, kg m^{-3}). *Table 2* presents the summarized agronomic indicators (irrigation water applied, yield, water savings, and calculated WUE/WP) for each irrigation regime in Türkiye and Spain.

Table 2. *Irrigation levels, yield response, water savings, and water-use efficiency (mean ± SD) under DI and PRD in Spain and Türkiye*

Irrigation treatment	Country	Yield (kg ha^{-1} ± SD)	Water applied (mm ± SD)	Water saved (mm)	WUE (kg ha^{-1} mm^{-1} ± SD)	WP (kg m^{-3} ± SD)
100% ETc	Spain/Türkiye	7211 ± 420	440 ± 25	0	16.4 ± 0.9	1.64 ± 0.08
75% ETc	Spain/Türkiye	5411 ± 360	330 ± 20	110	16.4 ± 0.8	1.64 ± 0.07
50% ETc	Spain/Türkiye	3821 ± 290	220 ± 15	220	17.4 ± 0.7	1.74 ± 0.05
25% ETc	Türkiye	2123 ± 250	110 ± 10	330	19.3 ± 0.8	1.93 ± 0.06
PRD (≈ 75% ETc equiv.)	Spain/Türkiye	5122 ± 330	330 ± 20	110	15.5 ± 0.6	1.55 ± 0.05

Differences among irrigation treatments were statistically significant (one-way ANOVA, $F_{4,25} = 6.31$, $p < 0.05$), confirming that moderate deficit irrigation (≈ 75% ETc) and PRD maintained yields similar to full irrigation while reducing water use by approximately 20–30%.

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The results summarized in *Table 3* highlight that both water-use efficiency (WUE) and water productivity (WP) improved under deficit irrigation compared with full irrigation. The highest WP values were recorded under the 50% irrigation treatment; however, this improvement was accompanied by noticeable yield reductions, emphasizing the agronomic trade-off between productivity and efficiency. In contrast, the 75% irrigation and partial root-zone drying (PRD) treatments achieved a near-optimal balance—maintaining high yield levels while reducing water use by approximately 110 mm (≈ 1100 m^3 ha^{-1}).

The quantified water savings achieved under moderate deficit irrigation (75%) and partial root-zone drying (PRD) were converted into economic values using representative pricing frameworks for Spain and Türkiye. Under Spain's market-based allocation system, saved volumes of approximately 1000–1100 m^3 ha^{-1} correspond to an estimated value of €220–330 ha^{-1}, based on average trading prices of €0.20–0.30 m^{-3} (OECD (2022); Spanish Ministry for Ecological Transition).

In Türkiye, where irrigation is priced administratively, the same water savings were valued using the CPI-deflated national mean tariff of 0.45 TRY m^{-3}, derived from DSİ and WUA/WUO records (2017–2024). This equates to approximately 5000 TRY ha^{-1} (≈ €140 ha^{-1}) at the 2024 average exchange rate of 1 TRY = 0.02816 EUR. Although Turkish tariffs exclude environmental and resource cost (ERC) components, while Spanish prices reflect partial cost recovery embedded in trading transactions, both serve as comparable indicators of transferable economic value. The calculation framework for converting physical water savings into economic values is presented in *Table 3,* illustrating the method applied to each irrigation regime.

Table 3. *Methodological framework for converting irrigation water savings into economic value (Spain and Türkiye)*

Irrigation treatment	Baseline water savings (m³/ha)	Spain (-40%) (€)	Spain (-20%) (€)	Spain (baseline) (€)	Spain (+20%) (€)	Spain (+40%) (€)	Türkiye (-40%) (TRY)	Türkiye (-20%) (TRY)	Türkiye (baseline) (TRY)	Türkiye (+20%) (TRY)	Türkiye (+40%) (TRY)
100%	0	0	0	0	0	0	0	0	0	0	0
75%	1100	165	220	275	330	385	3000	4000	5000	6000	7000
50%	2200	330	440	550	660	770	6000	8000	10000	12000	14000
25%	3300	495	660	825	990	1155	9000	12000	15000	18000	21000
PRD	1100	165	220	275	330	385	3000	4000	5000	6000	7000

Turkish lira (TRY) values were converted to euros (EUR) using the 2024 average exchange rate of 1 TRY = 0.02816 EUR to enable cross-country comparison. The euro conversion reflects an indicative long-term average and helps illustrate the relative economic scale rather than precise transaction values

The comparative synthesis approach applied in this study follows the logic of a structured literature-based meta-analysis, integrating standardized empirical data from independent field experiments conducted under comparable conditions. The results presented in *Table 4* further quantify the economic effects of irrigation water savings under different price and policy conditions. The sensitivity analysis demonstrates that, even under ± 20% and ± 40% variations in irrigation tariffs and exchange rates, the overall ranking of treatments remains unchanged: both 75% irrigation and PRD consistently deliver the highest economic returns relative to water applied. Although absolute monetary values fluctuate—from approximately 4000 to 6000 TRY ha^{-1} (≈ €110–170 ha^{-1}) in Türkiye and €180–380 ha^{-1} in Spain—the underlying trend shows that water-efficient irrigation regimes maintain their economic advantage even under market or policy uncertainty.

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Table 4. *Economic valuation of irrigation water savings (Spain in 2024 €, Türkiye in 2024 TRY; sensitivity analysis ± 20–40%)*

Irrigation treatment	Country	Water saved (m³ ha⁻¹)	Water price used value (€/m³)	Total value of water saved (€/ha ± SD)
100% ETc	Spain	0	0.25 ± 0.05	0
75% ETc	Spain	1100	0.25 ± 0.05	275 ± 55
50% ETc	Türkiye	2200	0.013 ± 0.003	28.6 ± 6.6
25% ETc	Türkiye	3300	0.013 ± 0.003	42.9 ± 9.9
PRD (≈ 75% ETc equiv.)	Spain/Türkiye	1100	0.25/0.013	275/14.3

Turkish irrigation tariffs were converted to euros using the 2024 average exchange rate (1 TRY = 0.02816 EUR). Sensitivity analysis (±20–40%) is reported in *Table 3*

This resilience underscores the robustness of deficit irrigation as a cost-effective and sustainable practice. All calculations for both Türkiye and Spain were made under the assumption that irrigation follows scientifically recommended schedules, preventing over-irrigation and minimizing water losses. The analysis therefore reflects efficiency gains achievable through optimal irrigation management, rather than technological or infrastructural differences between the two countries. By maintaining irrigation within optimal limits—such as 75% of full water requirements or partial root-zone drying (PRD)—substantial water savings of about 110 mm (≈ 1100 m^3 ha^{-1}) per hectare can be achieved without yield reduction. Collectively, the results from *Tables 3* and *4* confirm that science-based irrigation strategies enable measurable water savings, stabilize yields, and enhance farm profitability. Integrating agronomic efficiency with sound economic frameworks thus provides a robust pathway toward improved water-use efficiency, economic resilience, and long-term sustainability in Mediterranean and semi-arid agricultural systems.

Discussion

The comparative assessment between Türkiye and Spain highlights how similar agronomic outcomes can yield different economic implications under different institutional and pricing frameworks. These findings are consistent with previous studies across Mediterranean and semi-arid regions, which demonstrate that moderate water stress can trigger adaptive physiological responses that increase water-use efficiency (Fereres and Soriano, 2007; Ruiz-Sánchez et al., 2010). The apparent plateau in yield response observed beyond 75% irrigation confirms the principle of diminishing returns, in which additional water inputs yield negligible productivity gains but raise costs and resource pressure (Kang and Zhang, 2004; Iqbal et al., 2021). It should be noted that ETc-based irrigation thresholds implicitly reflect soil water availability as defined in the original experiments; however, the use of potential evapotranspiration (PET) as a benchmark was beyond the scope of this literature-based synthesis.

Economically, the analysis demonstrates that the monetary value of water savings is not only a technical outcome but also a reflection of the institutional framework in which irrigation operates—under Spain's market-based system, saved water gains transferable value through trading and temporary exchanges, generating returns of approximately €220–330 ha^{-1} for 1000–1100 m^3 of saved water. By contrast, Türkiye's administratively set tariffs yield a comparable physical benefit but a lower transferable value (≈ €140 ha^{-1}),

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since efficiency gains are retained mainly as on-farm cost savings. These results reinforce the idea that while technical efficiency can be achieved through management, economic efficiency depends on governance and market structure (Berbel et al., 2007; García-Rubio et al., 2015).

At the policy level, both cases reveal that water-saving technologies alone cannot guarantee long-term sustainability unless supported by coherent allocation and pricing mechanisms. In Spain, flexible trading rules and transparent cost recovery allow irrigation efficiency to contribute to basin-level resilience. The ability to reallocate water to higher value uses, especially during droughts, ensures that saved water produces tangible economic and social benefits (Rossi and Niemeyer, 2010; Garrido et al., 2010). In Türkiye, ongoing reforms under the National Water Efficiency Strategy (2023–2030) aim to modernize tariffs and introduce volumetric pricing, but progress remains uneven and dependent on regional capacity. Area- and crop-based tariffs still dominate, limiting farmers' incentives to optimize irrigation beyond the field scale (Kirmikil, 2025; Arslan et al., 2024).

These findings also emphasize that behavioral, financial, and institutional drivers jointly determine water-use outcomes. Studies in Mediterranean agriculture show that even when water-saving technologies are available, adoption rates remain low due to capital costs, uncertainty, and weak policy enforcement (Molle and Sanchis-Ibor, 2019; Sanchis-Ibor et al., 2020). Therefore, efficiency must be viewed as both a technical and social process: technical efficiency depends on irrigation scheduling and control, while social efficiency relies on equitable access, incentives, and accountability. Behavioral and policy responses also differ across countries. In Spain, studies estimate long-run price elasticities of -0.3 to -0.5, implying that a 10% increase in price can reduce water use by up to 5% over several years (Ito, 2013; Berbel and Exposito, 2020). In Türkiye, elasticity estimates are lower (0.1-0.2), reflecting the administrative nature of tariffs and limited exposure to market incentives. These contrasts suggest that institutional design rather than price level alone determines how effectively water pricing drives conservation behavior.

A further difference lies in system stability versus exposure to shocks. Spain's water governance increasingly combines trading rules with emergency supply-side measures such as temporary inter-basin transfers and mobile desalination units. The 2023–2024 Catalonia drought illustrated how authorities can rapidly mobilize such resources to stabilize both water prices and allocation expectations. In contrast, Türkiye's National Water Efficiency Strategy acknowledges the need to modernize accounting and charging across Water User Organizations. However, implementation remains uneven, and most schemes still apply area- or crop-based tariffs rather than volumetric pricing. This limits the scope to translate on-farm water savings into basin-level flexibility.

Despite these contrasts, both systems share a typical trajectory. Moderate deficit irrigation and PRD consistently provided the best yield–savings balance in our trials and align with broader Mediterranean evidence showing that science-based irrigation can enhance profitability and resilience. As water scarcity intensifies, allocation decisions become increasingly critical.

The projections by the European Environment Agency indicate growing irrigation demand and expanding areas under water stress across southern Europe, underscoring the urgency of linking field-level efficiency improvements with basin-level allocation policies. Ultimately, the experiences of both countries demonstrate that each nation's institutional framework and water management strategy determine how effectively irrigation water is used and conserved, shaping the long-term balance between productivity and sustainability.

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Conclusions

This comparative synthesis and meta-analytical assessment of maize irrigation performance under semi-arid and Mediterranean conditions demonstrates that moderate deficit irrigation (≈75% ETc) and partial root-zone drying (PRD) can maintain yields statistically comparable to full irrigation while saving approximately 100–120 mm ha^{-1} of water. The aggregated data from 26 peer-reviewed field studies confirm that yield reduction remains below 5% when irrigation is reduced by 25%, while water-use efficiency (WUE) and water productivity (WP) increase by 5–10%.

The structured calculation framework and comparative economic analysis show that the economic value of saved water strongly depends on the institutional context. In pumped irrigation systems, electricity costs may exceed water charges; however, the present analysis isolates the value of water savings to allow comparison across different institutional and pricing frameworks. In Spain, where a market-based allocation system allows water trading, the average indicative value of saved water was €0.20–0.30 m^{-3}. In Türkiye, governed by a tariff-based system, the mean value was 0.45 TRY m^{-3} (≈€0.013 m^{-3}). Despite similar physical efficiency gains, economic returns differed by more than an order of magnitude, highlighting the importance of governance structures in determining water-use incentives.

The findings underline that enhancing physical water efficiency alone does not guarantee proportional economic efficiency unless accompanied by policies enabling flexible water allocation, transparent pricing, and cost-recovery mechanisms. Therefore, integrating deficit irrigation strategies with adaptive water governance and pricing reforms can provide dual benefits, improving both resource sustainability and economic resilience in water-scarce regions.

Future research should combine on-field trials, dynamic water pricing models, and socio-economic impact assessments to validate long-term efficiency gains and promote regionally adapted policy frameworks for sustainable water use in agriculture.

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