Research

Eco-Efficiency of Irrigated Agriculture in Arid Oases: DEA Modelling of Moroccan Date Palm Farming

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Abstract

Arid oasis agriculture faces growing pressure to improve productivity while reducing water and energy use, raising concerns about whether irrigation modernization effectively enhances eco-efficiency under severe resource constraints. This study examines the technical and eco-efficiency of irrigated agriculture in arid oases, with a focus on Moroccan date palm farming. The objective is to evaluate how different irrigation systems shape productive and environmental performance and to identify the magnitude and sources of inefficiency. The analysis relies on farm-level survey data from 330 date palm farms in the Errachidia province and applies an input-oriented Data Envelopment Analysis (DEA) model under variable returns to scale, integrating an undesirable output capturing energy consumption related to irrigation. Results show marked efficiency gaps between irrigation systems: average technical efficiency reaches 0.789 for farms using localized irrigation compared with 0.549 under gravity irrigation, implying potential input savings of about 21% and 45%, respectively. Eco-efficiency outcomes indicate that localized irrigation reduces average water use (8,089 vs. 17,442 m^3/ha) and energy consumption (2,180 vs. 3,420 kWh/ha), yet substantial inefficiencies persist even among modernized farms. Overall, the findings demonstrate that technological upgrading alone does not guarantee eco-efficiency gains and that management practices and contextual constraints play a decisive role. By jointly addressing productivity and environmental pressures at the farm level, this study contributes to the literature on eco-efficiency measurement in arid agriculture and provides policy-relevant insights for designing irrigation modernization strategies aligned with sustainability objectives.

Statement of Sustainability: This study introduces an integrated eco-efficiency framework that jointly evaluates water, energy, and economic performance at the farm level in arid oasis agriculture. By embedding energy use as an environmental pressure within DEA modelling, the research advances operational tools for monitoring progress toward SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production). The findings support more resource-efficient irrigation strategies and inform sustainable agricultural policy design in water-scarce regions.

1. Introduction

Oasis ecosystems constitute a strategic socio-ecological space in Morocco, combining high agricultural value with strong environmental vulnerability. Located in arid and semi-arid regions, they play a key role in rural livelihoods, desertification control, and the productive use of scarce natural resources. Oases cover nearly 15% of the national territory, making their long-term sustainability a central challenge for Morocco's agricultural and territorial development (FAO, 2022; ADA, 2022). Within these ecosystems, date palm cultivation forms the backbone of oasis agriculture, supporting both economic activity and ecological regulation through diversified cropping systems adapted to harsh climatic conditions. However, these functions are increasingly threatened by water scarcity, climatic stress, and growing pressures to enhance agricultural productivity. As a result, improving agricultural performance while preserving environmental resources has become a major policy and research concern, particularly in water-scarce regions.

Over the past two decades, Moroccan date palm farming has expanded significantly under agricultural modernization policies. The

cultivated area increased from about 50,900 hectares in 2008 to nearly 69,500 hectares by 2025, reflecting sustained investments in irrigation infrastructure and plantation renewal (ADA, 2022; Chiabri & Bentahar, 2025). National production also increased, reaching an estimated 160,000 tons in the 2025–2026 season (Ministry of Agriculture, 2024). Despite this expansion, productivity remains highly heterogeneous across farms due to climatic variability and differences in management practices. Moreover, Morocco remains a relatively small producer compared with major date-producing countries such as Egypt, Saudi Arabia, Iran, and Algeria (FAOSTAT, 2022). Production is also spatially concentrated, with the Drâa-Tafilalet region accounting for nearly three-quarters of national output (ADA, 2022; FAO, 2022). These dynamics raise important questions about the efficiency with which resources are used in oasis agriculture.

To address productivity constraints, Morocco launched the Green Morocco Plan in 2009, promoting the modernization of irrigation systems and the development of more intensive agricultural models (ADA, 2011). Localized irrigation technologies were expected to improve water productivity and agricultural performance. However, in arid environments characterized by chronic water scarcity, the capacity of irrigation modernization to simultaneously enhance productivity and environmental sustainability remains debated. Increasing dependence on groundwater pumping has intensified energy consumption and environmental pressures. Consequently, agricultural performance can no longer be assessed solely in terms of output growth but must also consider the combined use of water and energy resources. This perspective aligns with the water–energy–food nexus framework, which emphasizes the interconnections between resource use, environmental impacts, and food production under climate stress (Yao et al., 2022).

From a theoretical standpoint, these challenges relate to the concept of productive efficiency, defined by Farrell (1957) as the ability of production units to maximize outputs given inputs. Economic efficiency results from the combination of technical and allocative efficiency (Atkinson et al., 1994a, 1994b). Data Envelopment Analysis (DEA) has become a widely used method to evaluate agricultural efficiency and environmental performance (Emrouznejad & Yang, 2018). Recent studies have extended DEA models to incorporate undesirable outputs, allowing a more comprehensive assessment of environmental sustainability (Dakpo et al., 2021; Picazo-Tadeo et al., 2021). Nevertheless, technological improvements may generate rebound effects, increasing overall resource use rather than reducing it, a phenomenon known as the irrigation efficiency paradox (Grafton et al., 2018). In response, the concept of eco-efficiency has emerged to evaluate the joint achievement of economic performance and environmental protection.

Despite a growing body of literature on agricultural efficiency, important gaps remain in arid oasis contexts. Existing studies often focus on techno-economic performance while neglecting environmental pressures related to water and energy use. Moreover, climatic constraints specific to arid environments are rarely incorporated into efficiency analysis, potentially confounding managerial inefficiency with natural limitations. Empirical assessments integrating both productivity and environmental dimensions at the farm level therefore remain limited.

Addressing these gaps, this study analyses the technical efficiency and eco-efficiency of date palm farms in the Errachidia province by comparing gravity and localized irrigation systems. Using an input-oriented Data Envelopment Analysis model with undesirable outputs related to energy use and based on farm-level survey data, the study evaluates whether irrigation modernization improves technical efficiency without necessarily ensuring eco-efficiency gains. The analysis aims to identify efficiency differentials and provide policy-relevant insights for more sustainable irrigation management in arid regions.

2. Materials and Methods

2.1. Study Area and Data

The empirical analysis is conducted in the province of Errachidia, located in the Drâa-Tafilalet region in south-eastern Morocco (Figure 1). This region represents the country's main date palm production basin, accounting for approximately 70–75% of national date output and hosting the majority of cultivated date palm areas (ADA, 2022; FAO, 2022). As such, Errachidia provides a highly relevant setting for examining efficiency and eco-efficiency issues in oasis agriculture, where production systems are simultaneously strategic for national food supply and highly vulnerable to environmental constraints.

Date palm farming plays a structuring role in the regional oasis agricultural system, both economically and socially. The date palm is the dominant perennial crop and constitutes a primary source of income and employment for local populations. Beyond its productive function, date palm cultivation contributes to household resilience, social stability, and the maintenance of traditional oasis systems in a context characterized by limited alternative livelihood opportunities and strong environmental stress (ADA, 2022; FAO, 2022). The performance of this sector is therefore closely linked to broader territorial sustainability outcomes in arid regions. Climatically, the study area is characterized by arid to hyper-arid conditions, with very low annual rainfall, high interannual variability, and elevated levels of potential evapotranspiration. These features make agricultural production highly dependent on irrigation and groundwater extraction (FAO, 2022). Under such conditions, water scarcity and energy requirements for pumping constitute critical constraints shaping farm performance. Consequently, the management of water and energy inputs becomes a central determinant of both productive efficiency and environmental pressure in oasis farming systems, particularly in a context of increasing stress on groundwater resources.
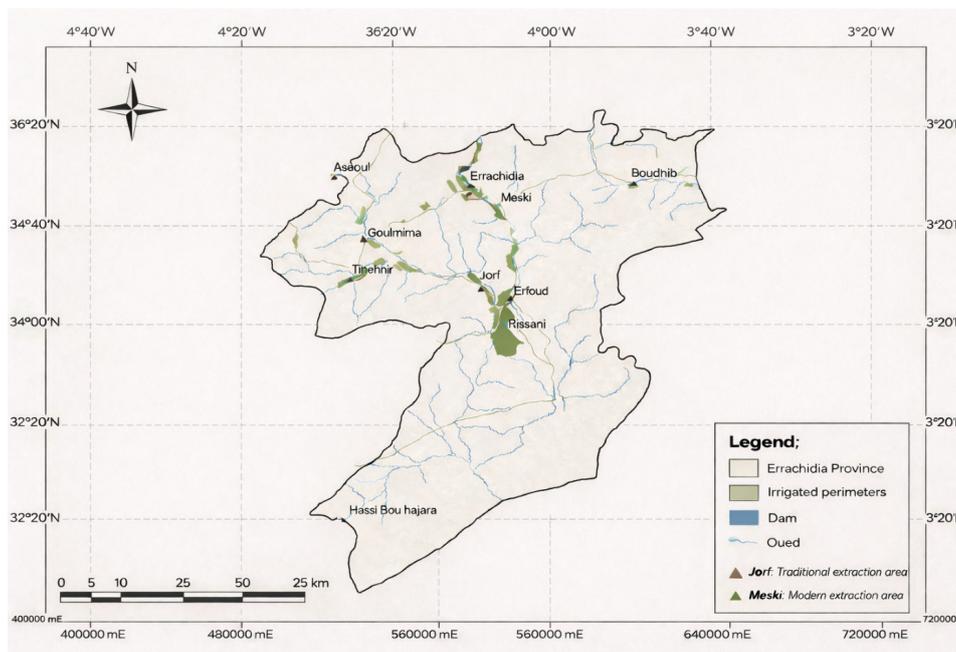
Figure 1. Location of the study area: Errachidia province (Drâa-Tafilalet region), south-eastern Morocco.
Source: Adapted from Ben-Said (2015).

The analysis focuses specifically on date palm farms, within which two irrigation systems coexist: traditional gravity irrigation and localized irrigation systems promoted under agricultural modernization policies. The coexistence of these systems generates substantial heterogeneity in production practices, input intensities, and performance levels. This diversity provides a suitable analytical framework for a comparative assessment of efficiency and eco-efficiency, allowing the effects of irrigation technology choices to be examined within a relatively homogeneous agro-ecological context.

Data used in the study are drawn from a field survey conducted among 330 date palm farms, which are treated as decision-making units (DMUs) in the efficiency analysis. Among the surveyed farms, 217 rely on gravity irrigation, while 113 use localized irrigation systems. Farm-level information was collected directly from producers and, where necessary, complemented with data from local agricultural services. This data collection strategy ensures a consistent and representative empirical basis capturing the structural and technological diversity of date palm farms in the Errachidia province.

2.2. Variables and Model Specification

2.2.1. Selection and Treatment of Variables

The model specification is based on a multi-input, multi-output representation of agricultural production units. To ensure comparability across farms and to avoid scale-related biases, all variables are expressed on a per-hectare basis. This normalization allows efficiency differences to be interpreted as reflecting managerial, technological, and environmental factors rather than farm size effects.

A: Inputs (m=3)

For each decision- making unit DMU j, the input vector is defined as Eq. 1:

$$Xj = (X1j, X2j, X3j) \tag{1}$$

where: $X_{1j:}$ denotes the volume of irrigation water used (m³/ha), which represents the main limiting factor in oasis agriculture; $X_{2j:}$ refers to the total production cost (MAD/ha), including expenses related to irrigation and energy, farm equipment installation and maintenance, agricultural inputs, and labor; $X_{3j:}$ corresponds to the area cultivated with date palms (ha), capturing structural constraints and potential scale effects.

B: Desirable outputs (S=2)

Productive and economic performance is captured through two desirable outputs (Eq. 2):

$$Yj = (Y1j, Y2j) \tag{2}$$

Where: Y_{1j} : is date production (tons/ha) ; Y_{2j} : is agricultural revenue (MAD/ha).

C: Undesirable output : environmental dimension

To explicitly integrate the environmental dimension into the efficiency analysis, one undesirable output is introduced: b_j: energy consumption related to irrigation (kWh/ha)

The choice of energy consumption as an undesirable output is conceptually grounded in the specific characteristics of oasis farming systems. In arid regions, most on-farm energy use is attributable to groundwater pumping, the intensity of which depends both on irrigation volumes and groundwater depth. Consequently, increased water use mechanically translates into higher energy consumption, which in turn generates indirect greenhouse gas emissions depending on the national energy mix. This relationship can be expressed as (Eq. 3):

$$Emissions \; j \; \propto \; E_j \times \gamma \tag{3}$$

Where E_j denotes the energy consumption of farm *j* and γ represents an average emission factor.

Within this framework, energy consumption serves as a relevant environmental proxy that operationalizes the water–energy–agriculture nexus and indirectly captures climate-related pressures associated with irrigation practices, without requiring direct measurement of CO_2 emissions, which are often unavailable at the microeconomic farm level. It should be noted, however, that this proxy does not account for all environmental externalities of irrigated agriculture, such as soil degradation or aquifer depletion, and relies on the assumption of a constant emission factor. Accordingly, energy consumption should be interpreted as a synthetic indicator of environmental pressure linked to irrigation rather than as a comprehensive measure of farms' carbon footprints. Despite these limitations, its inclusion allows for a coherent assessment of trade-offs between productive performance, water-use efficiency, and energy-related environmental pressure, which are central to sustainability challenges in arid oasis agriculture.

2.2.2. Orientation and Assumptions of the DEA Model

Efficiency analysis is conducted using an input-oriented DEA specification, as farmers exert greater control over input use (water, energy, land, and production costs) than over output levels, which are influenced by climatic variability and other exogenous factors. In arid oasis systems characterized by rainfall uncertainty and temperature extremes, this orientation is appropriate for identifying potential efficiency gains through input reduction while maintaining observed output levels.

The model is estimated under variable returns to scale (VRS) to account for structural heterogeneity across farms and to separate pure technical inefficiency from scale effects. A constant return to scale (CRS) specification is also estimated to derive scale efficiency through comparison with VRS scores, allowing assessment of whether farms operate at an optimal scale.

2.2.3. Mathematical Specification of DEA Model with an Undesirable Output

Consider a decision-making unit (DMU) *o* that uses an input vector $x_o \in \mathbb{R}+^3$ *to produce a vector of desirable outputs* $y_o \in \mathbb{R}+^2$ and one undesirable output $b_o \in \mathbb{R}_+$. Under an input-oriented specification with variable returns to scale (VRS), the DEA model is formulated as follows (Eq. 4):

$$\min_{\theta_0, \lambda} \theta_0 \tag{4}$$

Subject to (Eqs. 5-9):

$$\sum_{j=1}^{N} \lambda_j y_{rj} \geq y_{r0} \quad \forall r = 1, 2 \tag{5}$$

$$\sum_{j=1}^{N} \lambda_j b_j \leq b_0 \tag{6}$$

$$\sum_{j=1}^{N} \lambda_j x_{ij} \leq \theta_0 x_{i0} \quad \forall i = 1, 2, 3 \tag{7}$$

$$\sum_{j=1}^{N} \lambda_j = 1 \tag{8}$$

$$\lambda_j \geq 0 \quad \forall j \tag{9}$$

Where θ_0 is the efficiency score of DMU o, and $\lambda = (\lambda_1, \ldots, \lambda_N)$ is a vector of intensity variables defining the convex combination of observed DMUs that forms the reference frontier. The constraints ensure that the benchmark (i) produces at least the observed desirable outputs, (ii) does not exceed the observed undesirable output, and (iii) uses no more than a proportional fraction θ_0 of the observed inputs.

An efficiency score of $\theta_0 = 1$ indicates that the farm is both technically efficient and environmentally efficient (given the undesirable output), whereas a score $\theta_0 < 1$ reveals the potential to proportionally reduce inputs while maintaining desirable outputs and without increasing energy consumption related to irrigation.

2.2.4. Analytical Procedure and Comparison of Irrigation Systems

The efficiency and eco-efficiency scores derived from the DEA models are analyzed through a comparative framework distinguishing farm according to their irrigation technology. Specifically, efficiency outcomes for farms using traditional gravity irrigation are compared with those of farms adopting localized irrigation systems. This comparative approach makes it possible to assess how irrigation technology choices influence overall farm performance in terms of productive efficiency and environmental pressure.

The analysis focuses on differences in average efficiency scores, score distributions, and proximity to the efficiency frontier across the two groups of farms. By examining these patterns, the study identifies the extent to which irrigation modernization contributes to improved use of water and energy resources, as well as the magnitude of remaining inefficiencies. This procedure allows potential input-saving margins to be quantified for each irrigation system and provides empirical insights into whether localized irrigation systematically translates into higher levels of technical efficiency and eco-efficiency under arid oasis conditions.

2.2.5. Econometric Robustness and Validity of Efficiency Scores

Data Envelopment Analysis (DEA) constructs a non-parametric efficiency frontier based on observed best practices. In an input-oriented framework, the efficiency score measures the proportional reduction in inputs that is feasible while maintaining observed output levels. These scores are deterministic and conditional on the sample, reflecting relative rather than absolute performance.

Because DEA estimates are sample-dependent, results may be influenced by heterogeneity and extreme observations. Although bootstrap procedures have been proposed to correct potential bias in DEA estimates (Simar & Wilson, 2007), no empirical bootstrap correction was implemented in this study. The reported efficiency scores are therefore interpreted as deterministic, sample-dependent benchmarking measures rather than statistically unbiased population parameters.

In this study, robustness is enhanced through the use of a variable returns to scale (VRS) specification, allowing separation of pure technical inefficiency from scale effects. Efficiency scores are also computed under constant returns to scale (CRS) to assess scale efficiency through comparison with VRS results.

To improve comparability and limit scale distortions, all variables were expressed on a per-hectare basis. This normalization mitigates size-related effects and stabilizes the estimation of efficiency scores. Accordingly, the empirical analysis emphasizes comparative interpretation of score distributions and identification of benchmark farms rather than strict ranking. Efficiency scores are used as benchmarking tools to highlight potential margins for input reduction and eco-efficiency improvement, while acknowledging the structural and climatic constraints inherent to arid oasis farming systems.

3. Results

3.1. Descriptive Evidence and Structural Heterogeneity

Before assessing efficiency levels, it is necessary to examine the structural and production characteristics of the sampled farms. Descriptive statistics provide insight into differences in water use, cost structure, farm size, output levels, revenue generation, and energy consumption across irrigation systems. This step is essential to highlight the heterogeneity of production conditions and to justify the subsequent use of an input-oriented DEA model under variable returns to scale. The descriptive statistics are presented in Table 1.

The descriptive evidence reveals marked differences between irrigation systems. Water use under gravity irrigation exceeds 17,000 m^3 per hectare on average, more than twice the volume observed under localized irrigation. The dispersion of water consumption is particularly pronounced among gravity farms, where the standard deviation exceeds the mean, indicating extreme heterogeneity in irrigation practices. This variability suggests that inefficiencies are not solely technological but also managerial in nature.

Structural duality is equally evident. Localized irrigation farms are significantly larger, averaging 6.4 hectares compared with 2.1 hectares for gravity systems. This reflects the coexistence of fragmented traditional holdings and more consolidated modernized farms. The wide dispersion in farm size confirms that scale effects may influence performance outcomes and must therefore be accounted for in the efficiency assessment.

Productivity differences are moderate in physical terms but more substantial in economic terms. While yields are only moderately higher under localized irrigation, revenue per hectare is significantly greater, suggesting that modernization enhances not

Table 1. Descriptive statistics of date palm farms by irrigation system.

Variables	Gravity irrigation (n = 217)			Localized irrigation (n = 113)		
	Mean	**Std. Dev.**	**Min–Max**	**Mean**	**Std. Dev.**	**Min–Max**
Irrigation water (m^3/ha)	17,442	18,395	2,400 – 76,700	8,089	6,214	1,200 – 29,400
Total cost (MAD/ha)	68,540	72,118	12,600 – 311,200	94,320	61,840	25,000 – 280,000
Farm size (ha)	2.1	1.8	0.3 – 9.5	6.4	4.9	1 – 22
Production (t/ha)	7.8	3.6	1.2 – 18.4	9.6	4.1	2.3 – 21
Revenue (MAD/ha)	54,200	31,450	9,600 – 162,000	89,600	48,300	18,500 – 245,000
Energy (kWh/ha)	3,420	2,980	450 – 12,600	2,180	1,740	380 – 7,900

Source: Field survey, Errachidia province.

only output but also economic valorization. Energy consumption patterns reinforce the environmental dimension of performance. Gravity systems display higher energy intensity due to greater water extraction volumes and less efficient pumping infrastructure.

Taken together, these findings confirm substantial technical, economic, and structural heterogeneity across farms. This diversity justifies the adoption of a flexible non-parametric efficiency framework capable of capturing multiple dimensions of performance without imposing restrictive assumptions.

3.2. Efficiency Measurement and Comparative Performance

Having established the structural differences across irrigation systems, the analysis now turns to the measurement of technical, allocative, and economic efficiency using the input-oriented DEA model under variable returns to scale. This approach evaluates each farm relative to the best observed practices within the same agro-climatic context and identifies potential input-saving margins while maintaining output levels.

3.2.1 Average Efficiency Scores

The first step consists of examining average efficiency levels across irrigation systems. These scores provide a synthetic comparison of overall performance (Table 2).

Table 2. Average DEA efficiency scores by irrigation system.

Irrigation system	Technical efficiency	Allocative efficiency	Economic efficiency
Localized irrigation	0.789	0.916	0.856
Gravity irrigation	0.549	0.817	0.664

Source : DEA calculations (input orientation, VRS).

The results reveal a clear performance gap. Localized irrigation farms achieve substantially higher technical efficiency. A mean technical efficiency score of 0.789 implies that these farms could reduce inputs by approximately 21 percent without affecting output. In contrast, gravity-irrigated farms exhibit a much larger potential input reduction margin, approaching 45 percent.

Allocative efficiency differences further reinforce this pattern. Modernized farms combine inputs more effectively relative to their prices, particularly with respect to water and energy use. These advantages translate into significantly higher overall economic efficiency.

3.2.2. Distribution of Scores and Proximity to the Frontier

While average scores provide a general comparison, distributional analysis offers deeper insight into performance dispersion and proximity to the efficiency frontier (Table 3).

Table 3. Distribution of farms by technical efficiency class (in %).

Score class	Gravity irrigation	Localized irrigation
= 1	5	14
0.85 – < 1	18	31
0.70 – < 0.85	27	29
< 0.70	50	26
Total	100	100

Source : DEA calculations

Only a small fraction of farms operates on the frontier, particularly within gravity systems. More than half of gravity-irrigated farms

record efficiency scores below 0.70, indicating substantial input-saving potential. Localized irrigation farms are more concentrated in intermediate and higher efficiency classes, though heterogeneity remains significant. This confirms that modernization improves average performance but does not eliminate inefficiencies.

3.2.3, Benchmark Farms and Adjustment Margins

To better understand the characteristics of best-performing farms, the average profile of efficient localized irrigation units is examined (Table 4).

Table 4. Average characteristics of efficient localized irrigation farms.

Variables	Mean
Irrigation water (m^3/ha)	6,850
Total cost (MAD/ha)	71,300
Farm size (ha)	7.2
Production (t/ha)	12.4
Revenue (MAD/ha)	118,600
Energy (kWh/ha)	1,620

Source: DEA calculations

Efficient farms operating under localized irrigation exhibit a balanced combination of inputs, characterized by moderate water and energy consumption alongside strong economic valorization of output. Compared with the overall sample averages, these benchmark farms achieve higher yields and revenue levels while maintaining relatively controlled resource use. Their performance profile reflects not only technological adoption but also effective managerial practices in irrigation scheduling, input allocation, and production management (Table 5).

These farms define the empirical efficiency frontier and serve as operational benchmarks toward which inefficient farms may converge. The comparison with benchmark units allows potential adjustment margins to be identified, particularly in terms of water and energy reduction and improved input allocation. Rather than representing isolated cases, these efficient farms provide realistic and attainable performance standards within the same agro-climatic context. As such, they offer concrete guidance for improving both technical efficiency and eco-efficiency across irrigation systems in arid oasis agriculture.

Table 5. DEA projections for DMU 43 (localized irrigation).

Variables	Observed value	Projected value	Adjustment (%)
Irrigation water (m^3/ha)	21,500	2,210	-89.7
Total cost (MAD/ha)	198,400	8,700	-95.6
Farm size (ha)	11.3	1.7	-85.0
Production (t/ha)	8.9	8.9	0
Revenue (MAD/ha)	76,200	76,200	0

Source : DEA calculations

The case of DMU 43 illustrates a situation of pronounced input overutilization, particularly with respect to irrigation water and total production costs, without corresponding gains in output levels. The DEA projections indicate that substantial proportional reductions in inputs would be required for this farm to reach the efficiency frontier while maintaining the same production and revenue levels. Such results highlight the magnitude of potential adjustment margins and demonstrate the practical relevance of DEA-based benchmarking for identifying inefficient resource allocation patterns.

Efficient localized-irrigation farms define the empirical frontier and provide realistic benchmarking targets within the same agro-climatic setting (Table 4). Their average profile combines moderate irrigation water use (6,850 m^3/ha) and energy consumption (1,620 kWh/ha) with strong production (12.4 t/ha) and revenue levels (118,600 MAD/ha), suggesting that high economic performance can be achieved with controlled resource intensity. When a farm operates far from this frontier, DEA projections may imply large proportional input reductions, as observed for DMU 43 (Table 5).

All input and output variables were carefully rechecked for consistency in measurement units and were uniformly expressed per hectare to ensure comparability across farms and avoid scale distortions. The projected adjustments therefore reflect proportional efficiency targets derived from the best-performing units in the sample rather than data inconsistencies or scaling errors. Large percentage reductions may arise when a decision-making unit operates substantially below observed best practices, indicating a significant distance from the empirical frontier rather than unrealistic adjustment requirements.

Taken together, the findings show that irrigation modernization significantly improves both technical and economic efficiency

in date palm farming. However, the persistence of inefficiencies, even among farms using localized irrigation systems, indicates that technology adoption alone does not guarantee optimal performance. Achieving higher efficiency levels requires integrated management of water, energy, and other production factors. Beyond reporting efficiency scores and identifying benchmark farms, it is therefore necessary to examine the underlying mechanisms that explain performance disparities between irrigation systems.

3.3. Interpreting Efficiency Gaps between Irrigation Systems

The comparative results indicate that irrigation modernization significantly enhances average technical and economic efficiency. However, the persistence of inefficiencies among a considerable share of localized irrigation farms demonstrates that technological upgrading alone does not ensure convergence toward the frontier.

Several mechanisms may explain these gaps. In some cases, irrigation systems may be oversized or poorly managed, leading to excessive resource use. Structural constraints such as groundwater depth, soil conditions, and infrastructure quality may offset technological gains. Managerial capacity also plays a critical role, as localized irrigation requires technical expertise in scheduling and maintenance.

More broadly, efficiency disparities reflect the interaction between technology, structural characteristics, managerial behavior, and institutional incentives. Importantly, the DEA projections indicate that performance improvements are primarily achievable through input reduction rather than output expansion, a pattern typical of water-constrained agricultural systems.

Overall, the results demonstrate that irrigation modernization is a necessary but insufficient condition for sustained efficiency improvement. Achieving higher levels of technical and eco-efficiency requires integrated management of water, energy, and production factors within the specific constraints of arid oasis environments.

4. Discussion and Policy Implications

The empirical findings presented in the previous section call for a broader analytical interpretation that situates the results within the international literature on irrigated agriculture and resource efficiency in arid environments. Beyond the measurement of efficiency scores, it is essential to examine the structural mechanisms underlying observed performance gaps and to derive policy-relevant insights from the empirical evidence.

4.1. Discussion of Results in Light of the Literature

The DEA results confirm the existence of a structural efficiency gap between gravity and localized irrigation systems in date palm farming. This pattern is consistent with a substantial body of literature documenting the relative advantage of modern irrigation technologies in enhancing input control and improving technical efficiency in water-scarce environments (Frija et al., 2019; Gómez-Limón et al., 2020). The efficiency levels identified in this study fall within the range reported in Mediterranean and North African contexts (Dhehibi et al., 2021; Lachaal et al., 2022), reinforcing the empirical credibility of the technological effect observed.

However, the analysis moves beyond simply confirming the superiority of localized irrigation on average. A central contribution of this study lies in demonstrating that modernization does not automatically translate into full efficiency gains. A substantial share of farms equipped with localized irrigation systems remains below the efficiency frontier. This result aligns with research showing that the impact of water-saving technologies is mediated by managerial capacity, human capital, and contextual adaptation to local agro-climatic conditions (Karagiannis et al., 2018; Pérez-Urdiales et al., 2023). Technology adoption therefore constitutes a necessary but insufficient condition for improved performance.

The marked dispersion in water and energy use, especially within gravity irrigation systems, further indicates that inefficiency cannot be interpreted as purely technological. Institutional and behavioral dimensions play a decisive role. Weak incentive structures, limited enforcement of water-use regulation, and underdeveloped pricing mechanisms may encourage resource use patterns poorly aligned with marginal productivity, as documented in studies of agricultural water governance (Hellegers & Leflaive, 2015). In traditional oasis systems, additional structural characteristics such as land fragmentation, dependence on groundwater, aging hydraulic infrastructure, and informal governance arrangements reinforce performance heterogeneity.

At the same time, several mechanisms identified in this study extend beyond the Errachidia case. The conditional nature of modernization effects, the centrality of managerial competence, and the influence of institutional frameworks on resource allocation are widely observed across arid and semi-arid regions, particularly in North Africa and the Middle East. These findings contribute to the broader debate on the irrigation efficiency paradox by showing that technical improvements may be partially offset by behavioral, institutional, or hydrogeological constraints.

Moreover, the DEA projections indicate that performance improvements are primarily achievable through input reduction rather than output expansion. This pattern is characteristic of water-constrained agricultural systems (Grafton et al., 2018) and reinforces the relevance of adopting an eco-efficiency perspective that integrates the water–energy–agriculture nexus into performance evaluation.

While this eco-efficiency perspective highlights the central role of energy use within irrigated systems, it is important to acknowledge that energy consumption does not capture the full spectrum of environmental externalities associated with agriculture. Nevertheless, it represents a contextually relevant and operational proxy in arid oasis systems. In groundwater-dependent production environments such as those observed in Errachidia, irrigation intensity is directly linked to pumping energy requirements, which in turn generate indirect greenhouse gas emissions depending on the national energy mix. Energy use therefore reflects both resource pressure and environmental intensity within the water–energy–agriculture nexus. However, it does not account for other environmental dimensions such as soil salinization, aquifer depletion dynamics, or biodiversity impacts. The eco-efficiency assessment presented in this study should thus be interpreted as a partial but empirically measurable indicator of environmental performance at the farm level.

The results therefore suggest that sustainable modernization in arid environments requires a shift from productivity maximization toward resource optimization.

Having situated the empirical findings within the broader analytical and theoretical context, the discussion now turns to their operational implications for agricultural policy design and governance.

4.2. Policy Implications and Operational Recommendations

The differentiated efficiency outcomes observed across farms and irrigation systems imply that policy responses must be multilayered and coordinated across intervention scales. A purely technocentric approach to modernization is unlikely to generate sustained efficiency gains without complementary institutional and managerial reforms.

At the micro level, improving efficiency requires refined management of water and energy inputs. While localized irrigation reduces average resource use, the persistence of inefficiencies among modernized farms demonstrates that equipment alone is insufficient. Targeted training in irrigation scheduling, equipment maintenance, and adaptive management under climatic variability is essential to translate technological potential into effective performance gains. Strengthening farmers' technical capacities would help reduce input overutilization and enhance eco-efficiency without compromising output.

At the meso level, agricultural extension services and local governance institutions play a strategic role in diffusing best practices. The integration of DEA-based benchmarking tools into advisory systems could facilitate the identification of locally grounded performance standards. Because benchmarking relies on observed best practices within similar agro-climatic conditions, it can support peer learning and collective efficiency improvements. Such an approach may be particularly valuable in oasis systems where social networks and community-based water management structures remain influential.

At the macro level, the findings support a reorientation of agricultural modernization policies toward integrated frameworks combining technological investment, economic incentives, and regulatory mechanisms. Progressive pricing schemes for water and energy, carefully designed to avoid disproportionate impacts on small traditional farms, could strengthen incentives for rational resource use. Simultaneously, incorporating explicit eco-efficiency criteria into policy evaluation frameworks would allow productivity objectives to be aligned with water sustainability and energy transition goals.

In this perspective, modernization should not be conceived solely as technological upgrading but as systemic transformation encompassing institutional design, incentive structures, and human capital development. Such an integrated approach is necessary to ensure that irrigation modernization contributes effectively to sustainable agricultural development in arid and water-constrained regions.

5. Conclusion

This study provides an integrated evaluation of technical efficiency and eco-efficiency in date palm farming within an arid oasis context, using an input-oriented DEA framework incorporating energy consumption as an undesirable output. The comparison between gravity and localized irrigation systems in Errachidia province reveals clear structural performance differences. Localized irrigation farms achieve higher average technical and economic efficiency, yet a significant share of modernized farms remains below the efficiency frontier.

These findings demonstrate that technological upgrading alone does not guarantee performance improvement. Efficiency outcomes are strongly conditioned by managerial capacity, structural constraints, and institutional settings. Improvement margins are primarily associated with optimizing water and energy use rather than expanding output, underscoring the importance of an eco-efficiency perspective in water-scarce agricultural systems.

From a policy standpoint, the results support a shift toward integrated modernization strategies that combine technological investment with targeted technical support and incentive-based resource regulation. Incorporating DEA-based benchmarking tools into agricultural policy evaluation may enhance locally adapted performance standards. Although the deterministic nature of DEA and the use of energy as an environmental proxy require cautious interpretation, the study offers robust empirical insights for designing more efficient and sustainable irrigation policies in arid regions.

Declarations

Conflicts of interest: The author declares no conflict of interest.

Ethics approval: The study was conducted in accordance with standard ethical principles for social science research. Participation in the survey was voluntary, and respondents were informed about the purpose of the study. No personal identifying information was collected or retained. No formal institutional ethics committee approval was required for this research.

Consent for publication: The author has read and approved the final version of the manuscript.

Data availability: The data supporting the findings of this study are available from the author upon reasonable request.

Supplementary material: No supplementary material is associated with this manuscript.

Additional information: No additional information is associated with this study.

References

Agence pour le Développement Agricole (ADA). (2011). Plan Maroc Vert : Bilan et perspectives de la filière phoenicicole. Ministère de l'Agriculture et de la Pêche Maritime, Royaume du Maroc.

Agence pour le Développement Agricole (ADA). (2022). La filière du palmier dattier au Maroc : État des lieux et enjeux de développement. Ministère de l'Agriculture, de la Pêche Maritime, du Développement Rural et des Eaux et Forêts.

Atkinson, S. E., Cornwell, C., & Honerkamp, O. (1994a). Measuring and decomposing productivity change: Stochastic frontier estimation versus data envelopment analysis. *Journal of Business & Economic Statistics*, *12*(3), 283–296.

Atkinson, S. E., Cornwell, C., & Scott, J. T. (1994b). Measuring productive efficiency: Techniques and applications. *Journal of Econometrics*, *61*(2), 299–317.

Ben-said, E. H. (2015). Etude hydrogéologique et élaboration d'une base de données spatiale du bassin Crétacé de la province d'Errachidia. Mémoire de fin d'études, Université Sidi Mohammed Ben Abdellah, Faculté des Sciences et Techniques, Fès, 78 p.

Chiabri, L., & Bentahar, A. (2025). Territorial Governance and Inclusive Development in Drâa-Tafilalet's Date-Palm Sector: Assessing the Green Morocco Plan. *AgroEnvironmental Sustainability*, *3*(3), 198-209. https://doi.org/10.59983/s2025030303

Dakpo, K. H., Jeanneaux, P., & Latruffe, L. (2021). Modelling pollution-generating technologies in performance benchmarking: Recent developments and future prospects. *European Journal of Operational Research*, *289*(2), 347–363. https://doi.org/10.1016/j.ejor.2019.07.009

Dhehibi, B., Frija, A., Aw-Hassan, A., & Lassoued, N. (2021). Water use efficiency and productivity in irrigated agriculture: Evidence from North Africa. *Agricultural Water Management*, *245*, 106645. https://doi.org/10.1016/j.agwat.2020.106645

Emrouznejad, A., & Yang, G. (2018). A survey and analysis of the first 40 years of scholarly literature in data envelopment analysis. *Socio-Economic Planning Sciences*, *61*, 4–8. https://doi.org/10.1016/j.seps.2017.01.008

Farrell, M. J. (1957). The measurement of productive efficiency. *Journal of the Royal Statistical Society: Series A (General)*, *120*(3), 253–290. https://doi.org/10.2307/2343100

Food and Agriculture Organization of the United Nations (FAO). (2022). FAOSTAT: Crops and agricultural production statistics. https://www.fao.org/faostat/

Frija, A., Dhehibi, B., & Gomez y Paloma, S. (2019). Improving water productivity in irrigated agriculture: Lessons from efficiency analysis in Mediterranean countries. *Water Resources Management*, *33*(6), 2079–2094. https://doi.org/10.1007/s11269-019-02229-0

Gómez-Limón, J. A., Picazo-Tadeo, A. J., & Reig-Martínez, E. (2020). Eco-efficiency assessment of olive farms in Andalusia. *Land Use Policy*, *95*, 104611. https://doi.org/10.1016/j.landusepol.2020.104611

Grafton, R. Q., Williams, J., Perry, C. J., Molle, F., Ringler, C., Steduto, P., & Udall, B. (2018). The paradox of irrigation efficiency. *Science*, *361*(6404), 748–750. https://doi.org/10.1126/science.aat9314

Hellegers, P., & Leflaive, X. (2015). Water allocation reform: What makes it so difficult? *Water International*, *40*(2), 273–285. https://doi.org/10.1080/02508060.2015.1025196

Karagiannis, G., Tzouvelekas, V., & Xepapadeas, A. (2018). Measuring irrigation water efficiency under environmental constraints. *European Review of Agricultural Economics*, *45*(2), 287–317. https://doi.org/10.1093/erae/jbx030

Lachaal, L., Dhehibi, B., & Frija, A. (2022). Irrigation water use efficiency and sustainability challenges in North African agriculture. *Water Policy*, *24*(6), 1051–1068. https://doi.org/10.2166/wp.2022.214

Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests. (2024). Forecasted date production for the 2024–2025 agricultural season. Kingdom of Morocco.

Pérez-Urdiales, M., García-Garizábal, I., & Merino-de-Miguel, S. (2023). Irrigation modernization and farm efficiency: A DEA-based assessment. *Agricultural Water Management*, *276*, 108037. https://doi.org/10.1016/j.agwat.2022.108037

Picazo-Tadeo, A. J., Gómez-Limón, J. A., & Reig-Martínez, E. (2021). Assessing farming eco-efficiency: A review of methodological approaches. *Agricultural Systems*, *189*, 103066. https://doi.org/10.1016/j.agsy.2021.103066

Simar, L., & Wilson, P. W. (2007). Estimation and inference in two-stage semi-parametric models of production processes. *Journal of Econometrics*, *136*(1), 31–64. https://doi.org/10.1016/j.jeconom.2005.07.009

Yao, L., Zhang, Y., & Wang, R. (2022). Water–energy–food nexus efficiency in irrigated agriculture under climate stress. *Science of the Total Environment*, *807*, 150812. https://doi.org/10.1016/j.scitotenv.2021.150812