

Article

Assessing Sustainability of Oasis Systems in Southern Tunisia

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Abstract

The sustainability of date palm cultivation is a critical research focus due to its vital role in food security and the resilience of agricultural systems in arid regions. This study evaluates the sustainability of date palm farms by examining how distinct oasis typologies, traditional and modern, influence three core dimensions: agro-ecological, socio-territorial, and economic. Employing the IDEA framework (Indicateurs de Durabilité des Exploitations Agricoles) and statistical analyses, field data from 60 farms in Tunisia's Tozeur and Kebili regions were assessed. The results revealed marked heterogeneity in sustainability performance, strongly structured by oasis type. Traditional oases exhibited higher agro-ecological sustainability but greater economic vulnerability, while modern oases proved more economically robust yet less environmentally sustainable. These findings highlight a clear trade-off between environmental integrity and economic performance, highlighting the need for differentiated strategies to enhance the overall sustainability of oasis agricultural systems.

Keywords: date palm; oasis systems; sustainability; IDEA method; traditional oasis; modern oasis; Southern Tunisia

1. Introduction

The agricultural sector worldwide contends with multifaceted and interconnected challenges. Date palm (*Phoenix dactylifera* L.) cultivation, while uniquely adapted to arid Saharan climates, faces intensifying pressures from escalating water scarcity. Beyond its agronomic role, this sector is fundamental to the socio-economic stability of rural communities, serving as a critical source of employment and income. In Tunisia, for instance, date palm farming generates approximately 2.5 million workdays annually, accounting for an estimated 9% of total agricultural employment [1], thereby underpinning livelihoods and regional economic viability.

Date palm cultivation represents a cornerstone of Tunisia's irrigated agriculture and a significant contributor to international trade. The sector is vital for the livelihoods of nearly 12,000 farmers across four governorates (Gabes, Tozeur, Kebili, and Gafsa), with oasis systems covering approximately 15% of the nation's total irrigated land. Globally, date production increased markedly from 4.4 to 7.2 million tons between 1993 and 2014, with Asia (63.9%) and North Africa (35.5%) dominating supply [2]. During this period, Egypt (16%), Iran (15%), and Saudi Arabia (13%) led in production volume. While Tunisia accounts for only about 4% of the world's cultivated date palm area, ranking sixth among



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exporting nations, it holds a disproportionate position in global trade. The country is the world's leading exporter by value, generating approximately 24% of global export revenues, thereby outperforming larger producers in the premium market [2].

The significance of Tunisia's date palm sector is further magnified by evolving international market dynamics. Global date trade has demonstrated consistent expansion, with annual trade volumes growing at approximately 10%. South Asia and the Middle East remain primary importing regions, while Europe constitutes the second-largest market, accounting for roughly 15% of global imports. Within Europe, demand has risen steadily, particularly in France and the United Kingdom. France, as the continent's leading consumer, re-exports approximately 30% of its imports, predominantly to other European markets. Conversely, consumption in the United Kingdom is largely driven by its substantial diaspora communities with cultural ties to date-producing regions. These dynamics reinforce the strategic importance of Tunisia's date sector within global premium markets.

Despite its significant economic and social contributions, oasis-based date palm cultivation in southern Tunisia faces mounting threats to its long-term viability. These systems are increasingly vulnerable to a nexus of environmental pressures, primarily water scarcity, soil salinization, and climate variability, compounded by socio-economic challenges such as market dependency and rural outmigration. Consequently, a comprehensive, multi-dimensional assessment of the sustainability of these agroecosystems has become imperative to ensure their resilience and inform adaptive management strategies.

Indicator-based sustainability assessment is widely recognized as a prerequisite for informed farm management and the formulation of robust farm management strategies [3]. Contemporary frameworks predominantly conceptualize farm-level sustainability around three interdependent dimensions: economic viability, social equity, and ecological integrity [4]. The literature reflects a proliferation of methodological approaches, with over sixty distinct indicator-based frameworks reported [5]. A detailed review is beyond the scope of this paper; however, it is worth noting that simulation models such as APSIM have been used to evaluate cereal farm sustainability [6], while comparative studies have assessed the performance of different cropping systems [7].

Among the various assessment tools, the IDEA framework (*Indicateurs de Durabilité des Exploitations Agricoles*) has emerged as one of the most extensively applied multi-criteria methods within the European Union [8,9]. Valued for its comprehensive multi-dimensional structure and operational practicality, it has also been validated in North African contexts [10–12]. For example, Attia et al. [13] successfully employed IDEA to assess the sustainability of small-scale dairy farms across different production systems in northern Tunisia. Research on agricultural sustainability in Tunisia has encompassed diverse systems, including dairy farming [13,14], a comparison of organic and conventional production [15], irrigated systems in arid regions [16], and olive production [17]. However, despite their acknowledged ecological and socio-economic significance, research specifically assessing the sustainability of oasis-based agroecosystems remains notably limited.

This gap is particularly critical given that Tunisia's date palm yields per hectare remain substantially below those of other leading producer nations. The average yield for the premium Deglet Nour variety ranges from 2700 to 3000 kg/ha, contrasting with averages of 4000–7000 kg/ha in countries like Iran, Saudi Arabia, and the United States. Consequently, Tunisia records the lowest productivity per unit of land among the world's top date-exporting countries. These pronounced yield gaps underscore critical questions about the underlying agronomic, economic, and environmental sustainability of oasis farming systems in the region.

While previous research has applied the IDEA framework to various Tunisian agricultural systems, no study has systematically compared the multi-dimensional sustainability

of traditional versus modern oasis systems using a context-adapted version of this tool. This study provides the first empirical evidence of a systemic sustainability trade-off between these two development models in Tunisia's date sector. By quantifying this divergence and identifying its structural determinants, particularly farm size and production specialization, the analysis offers a diagnostic foundation for differentiated policy interventions. It further demonstrates how a standardized sustainability assessment framework can be meaningfully adapted to the specific socio-ecological constraints of arid agroecosystems.

Specifically, the study tests the following three hypotheses:

H1. The three sustainability dimensions, agro-environmental, socio-territorial, and economic, respond differentially to the defining structural and managerial characteristics of traditional and modern oasis types.

H2. Modern oasis systems achieve higher economic sustainability scores than traditional systems.

H3. Larger farm size is positively associated with higher overall sustainability scores, with this relationship being more pronounced in modern oasis systems.

2. Methods

2.1. IDEA Framework for Assessing Farm Sustainability and Contextual Adaptation

The sustainability of date palm farms in Tunisia's Saharan regions was assessed using the IDEA framework (Indicateurs de Durabilité des Exploitations Agricoles). This method enables a comprehensive, farm-level evaluation through a structured set of indicators spanning agro-ecological, socio-territorial, and economic dimensions. In line with the protocol established by [18], all farm data were collected voluntarily and anonymously from participating farmers.

Sustainability indicators function as measurable proxies for complex system properties, providing an integrated view of farm performance to inform management and policy decisions [19]. Initially conceived as an educational tool, the IDEA framework has evolved into a robust multi-criteria assessment system widely applied in agricultural research and policy analysis [5,9].

The framework has undergone significant iterative refinements. The current version, IDEAv4, represents a comprehensive update that aligns its evaluative grids with contemporary sustainability challenges [5]. A principal strength of the method is its diagnostic sensitivity, which allows it to detect variations in sustainability performance across different farm scales and production systems [20].

For this study, the standard IDEAv4 framework was adapted to the specific socio-ecological context of Tunisian oases in consultation with local agronomists and extension agents.

Key adaptations included:

1. **Agro-Environmental Dimension:** The scoring for the water source indicator (A7) was modified to accurately reflect the prevalence, management, and sustainability challenges associated with collective groundwater wells (Agricultural Development Groups GDAs) compared to individual wells.
2. **Economic Dimension:** Thresholds for the 'commercial vulnerability' indicator (C2) were adjusted to account for the high degree of market concentration and dependence of Tunisian date farms on a limited number of export channels.
3. **Socio-Territorial Dimension:** The 'social involvement' indicator (B4) was explicitly structured to recognize formal membership and active participation in key local institutions, such as GDAs and the national farmers' union (UTAP).

These targeted adaptations ensured the indicator set remained relevant, sensitive, and capable of capturing the key determinants of sustainability within the distinct context of Tunisian oasis agriculture, thereby enabling a tailored and meaningful evaluation.

2.2. Mathematical Framework of the IDEA Method

The IDEA methodology operationalizes sustainability through a structured set of indicators distributed across three core dimensions: agro-environmental, socio-territorial, and economic. Each indicator is assigned a quantitative score based on standardized evaluative grids, detailed in subsequent sections. The overall score for a given sustainability dimension is calculated by summing the scores of its constituent indicators, with each dimension having a theoretical maximum of 100 points.

The total sustainability score for a given farm j is expressed as follows:

$$\text{Total sustainability (Farm } j) = \sum_{k=1}^3 \sum_{i=1}^{n_k} \text{scores}_{ik}$$

k = dimension of sustainability (1 = economic, 2 = agro-environmental, 3 = social);

i = indicator within dimension k ;

j = index of the farm;

n_k = number of indicators in dimension k ;

scores ikj = score assigned to indicator i in dimension k for farm j .

Economic dimension

The economic dimension assesses a farm's capacity to ensure long-term viability, maintain financial autonomy, and operate efficiently. It evaluates the ability to generate sufficient income, mitigate financial risk, and sustain profitability amidst fluctuating environmental and market conditions.

For this study, economic sustainability was evaluated using four key indicators: (i) economic viability, (ii) commercial vulnerability, (iii) financial autonomy, and (iv) production process efficiency. Aggregated, these indicators provide a comprehensive assessment of the farm's financial health and economic resilience.

A farm achieving high cumulative scores demonstrates robust economic sustainability, characterized by a strong ability to generate adequate income per labor unit, diversify production and marketing to buffer risks, maintain independence from external credit, and utilize inputs efficiently. In contrast, farms with lower scores are more vulnerable to external shocks, such as price volatility, climatic stress and financial instability.

Agro-environmental dimension

The agro-environmental dimension appraises the ecological integrity of the farming system and its capacity to sustain production while preserving natural capital. It is operationalized through eight indicators, each targeting a specific aspect of environmental performance. These indicators collectively measure key systemic properties, including the maintenance of biodiversity, the stewardship of soil and water resources, the efficiency of input use, and the degree of energy dependency.

Consequently, farms achieving high scores in this dimension are characterized by practices that enhance ecological resilience, such as crop diversification, minimal reliance on synthetic chemical inputs, the adoption of efficient irrigation and soil conservation techniques, and a preference for renewable or low-impact energy sources.

Socio-territorial dimension

The socio-territorial dimension evaluates a farm's contribution to social equity, local development, and the quality of life for farmers and their communities. This dimension is measured through seven indicators, each addressing a distinct facet of the farm's social and territorial embeddedness. The indicators collectively assess a range of factors, including product quality and traceability, engagement with short supply chains, em-

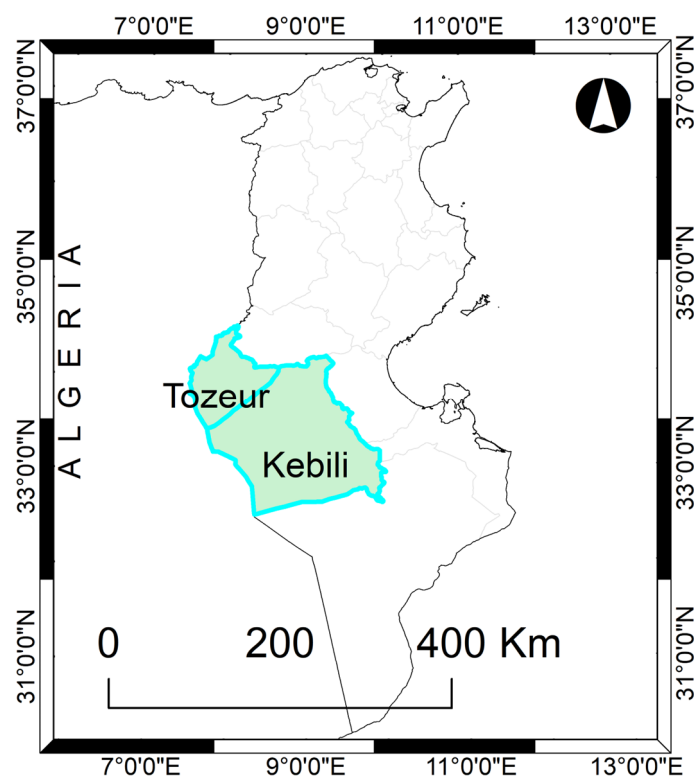
ployment generation and working conditions, social participation, access to training, and livelihood diversification.

2.3. Study Area

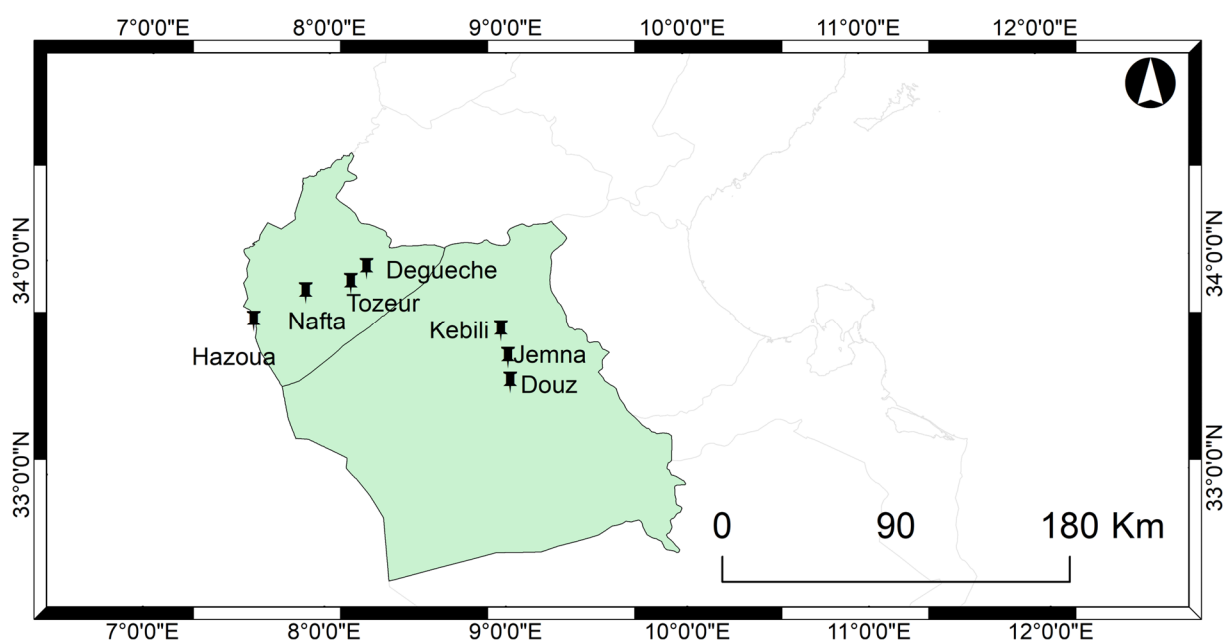
Oasis agroecosystems in Tunisia are broadly categorized into two principal types based on their historical development and management paradigms: traditional and modern oases. According to the most recent national inventory, Tunisia comprises 267 distinct oases, with traditional systems accounting for 126 units (~15,000 ha) and modern systems for 141 units (~40,000 ha).

Traditional oases occupy nearly one-third of the national oasis area and are predominantly located in the governorates of Tozeur, Kebili, Gabes, and Gafsa, supporting an estimated 5.5 million date palms. These systems are defined by a stratified, multi-layered agroforestry structure: a lower herbaceous layer, a middle stratum of fruit trees and an upper canopy of date palms planted at high density (200–220 palms ha⁻¹). This configuration fosters a favorable microclimate, reduces soil evaporation, optimizes resource use and sustains significant agrobiodiversity. Irrigation is traditionally supplied by gravity-fed systems (*seguias*), supporting diverse, locally adapted crop varieties that collectively enhance on-farm food security and socio-ecological resilience. However, traditional oases face mounting systemic challenges, including land fragmentation, palm grove senescence, inadequate maintenance and the over-exploitation of groundwater resources.

In contrast, modern oases represent the outcome of deliberate national development policies aimed at enhancing date production and economic returns. These systems are primarily concentrated in the inland governorates of Kebili and Tozeur (Map 1; Map 2). Their defining characteristics include uniformly spaced monoculture plantations of the high-value Deglet Nour variety, with plot sizes typically ranging from 1 to 5 hectares and planting densities of 100–120 palms per hectare. Production relies on pressurized irrigation systems and mechanized operations, reflecting a specialized, market-driven model. The rapid expansion of modern oases in recent decades has been facilitated by targeted state-led development programs, which have also coincided with a notable shift away from traditional date cultivation in other regions like Gabes and Gafsa, often in favor of vegetable, forage and olive crops. Nonetheless, within the core production areas, Deglet Nour cultivation remains exceptionally profitable, constituting approximately 90% of the total economic value generated by Tunisia's date sector.



Map 1: Main regions of palm oasis concentration in Tunisia



Map 2: Locations of sampled sites used in this study.

2.4. Data Collection and Sampling

This study is based on primary data collected through field surveys conducted in 2023 from 60 date-producing farms in the governorates of Tozeur and Kebili, the primary date-producing regions of Tunisia (Map 2). A stratified random-sampling design was employed to ensure representative coverage of the two principal oasis typologies (traditional and modern) and variation in farm size across the study area. The sampling framework was developed in collaboration with the Regional Commissions for Agricultural Development

(CRDAs) to ensure a balanced representation of oasis type, geographic distribution, and operational scale (Table 1).

Table 1. Distribution of oasis area and sampled farms disaggregated by governorate and oasis type.

	Traditional Oases		Modern Oases	
	Area	Share of Total National Oasis Area	Area	Share of Total National Oasis Area
Gafsa	3388	18.2	936	2.5
Tozeur	3576	19.2	4828	12.7
Gabes	7325	39.3	0	0.0
Kebili	4350	23.3	32,210	84.8
Tunisia	18,639	100	37,974	100
Number of plots per oasis type	35,098	58.5	24,925	41.5
Number of employment count (days): 9.6 million working days				
Oasis population (number): 280,000 people				

Source: [21].

The target sample size of 60 farms was determined to ensure adequate representation of the main strata while remaining logistically feasible for in-depth data collection. Based on regional agricultural census data [21], this sample represents a significant proportion of the commercial date farm population in the core study regions. While stratified random sampling improves representativeness, potential biases are acknowledged. These include an accessibility bias, as remote farms were more challenging to reach, and a possible under-representation of very small, subsistence-oriented farms less engaged with formal extension services. Consequently, the sample is most representative of market-oriented date production systems. Practical field constraints, including accessibility and farmer availability, led to an adjustment of the initial sampling plan, resulting in the final sample of 60 farms.

In parallel, three focus group discussions (FGDs) were conducted with lead farmers and key local stakeholders in representative oases. These discussions provided qualitative insights into management practices, resource use challenges and perceptions of sustainability, thereby complementing and contextualizing the quantitative survey data.

The structured survey instrument was designed to capture the key socio-economic, agronomic and environmental characteristics of the farms and consisted of four main sections:

1. Socio-economic characteristics: Farmer age, education, household structure, income sources and access to resources.
2. Agro-environmental indicators: Land tenure, water resources and irrigation practices, and perceived environmental conditions.
3. Agronomic practices: Crop diversification, input use (fertilizers, pesticides) and farm management techniques.
4. Economic performance: Production volumes, yields, marketing channels and farm income for the 2022–2023 agricultural year.

Following data collection, all responses underwent systematic verification and standardization procedures to ensure internal consistency and comparability across oasis types within study regions.

2.4.1. Agro-Environmental Sustainability Dimension

The agro-environmental dimension was assessed using eight indicators covering crop and animal diversity, land and livestock management, input use, soil and water

conservation and energy dependence, as detailed in Table 2. These indicators collectively capture the environmental performance and resource use efficiency of date palm farming systems.

Table 2. Agro-environmental sustainability indicators, calculation methods, and scoring criteria for farm operation.

Indicators	Components	Calculation Method	Principal Characteristics of Operations
A1—Crop diversity	• Cultivated species (annual and perennial)	Number of cultivated species: • Less than or equal to two: 2 • Between 2 and 4 species: 4 • More than 4 species: 8	Producing fruit and vegetables for personal consumption
	• Area of perennial crops as a percentage of UAA Area	Area representing • Less than 10% of UAA: 2 • Between 10 and 20% of UAA: 6 • More than 20% of UAA: 10	100%
A2—Animal diversity	Species (Number)	2 points per species present: 10	No livestock
A3—Plot management	Average plot size	Average plot size • Less than 2 ha: 6 • Between 2 and 3 ha: 4 • More than 3 ha: 2	Farms between 2 and 3 ha, with a few farms having more than 3 ha
	• Area of the largest spatial unit of the same crop	• Greater than 2 ha: 2 • Between 1 and 2 ha: 4 • Less than 1 ha: 6	The largest plot is 2 ha
A4—Livestock density and forage management	• Livestock density	Livestock density: LU/forage area (ha) • Less than 0.5 LU/ha: 6 • Between 0.5 and 2 LU/ha: 4 • More than 2 LU/ha: 0	No livestock
	• Grazing area as a percentage of UAA	Area reserved for grazing: • Less than 10% of UAA: 2 • More than 10% of UAA: 4	Less than 0.1 ha
A5—Fertilization and organic-matter management	• Share of legume area percentage of UAA	Presence of legumes: • Less than 10% of UAA: 0 • Between 10 and 20% of UAA: 2 • More than 20% of UAA: 4	Just for self-consumption (10–20%)
	• Valorization of organic-matter (manure, compost) Area/of UAA	• No composting: 0 • Less than 25% of UAA: 2 • Between 25% and 50% of UAA: 6 • More than 50% of UAA: 8	Use of organic fertilizers
	• Fertilizer application (quantity and area)	Quantity of mineral fertilizer applied per ha: • Less than 20 kg/ha: 6 • Between 20 and 50 kg/ha: 4 • Between 50 and 80 kg/ha: 2 • More than 80 kg/ha: 0	Uses sulfur

Table 2. Cont.

Indicators	Components	Calculation Method	Principal Characteristics of Operations
A6—Use of pesticides and veterinary products	• Area treated with plant protection products	Pollution pressure (PP) = Treated area/UAA	Plant protection treatment between 25–50%
		• No treatment: 6	
		• PP less than 25%: 4	
		• PP between 25 and 50%: 2	
		• PP between 50% and 75%: 1	
		• PP between 75% and 100%: 0	
	• Number of veterinary interventions	• Number of VIs less than or equal to 2: 4 • Number of veterinary interventions between 2 and 3: 2 • Number of veterinary interventions greater than 3: 0	Without treatment
A7—Soil and water management	• Tillage without turning	Area that has undergone tillage without turning:	Tillage between 3 and 4 years
		• Less than 25% of UAA: 4	
		• Between 25% and 50% of UAA: 2	
		• More than 50% of UAA: 1	
	• Anti-erosion and landscaping measures	Landscaping structures (hedges, grass strips, etc.) or soil mulching on:	Landscaping with date palms
		• Absence (0% of UAA): 0	
		• Presence on less than 25% of cultivated area: 2	
		• Presence on more than 25% of cultivated area: 4	
	• Irrigation	Absence of irrigation: −1	Installation of a new drip irrigation system
		• Gravity irrigation throughout the farm: 2	
		• Localized/drip irrigation on less than 50% of UAA: 4	
	Irrigation water source	• Localized/drip irrigation on more than 50% of UAA: 6	• Pumping from GDA wells
		• Irrigation from collecting rainwater, drainage or runoff: 2	
		• Individual pumping, undeclared and/or not: −1	
A8—Energy dependence	• Fuel consumption in liters	• Less than 50 L/hectare/year: 2	Under STEG networks
		• Between 50 and 100 L/hectare/year: 1	
		• More than 100 L/hectare/year: 0	
		• Between 10 and 20/hectare/year: 1	
		• More than 20/hectare/year: 0	
	• Renewable energy	• Renewable energy source (solar energy, wind energy) = 2	Not currently installed for the GDA

UAA: Agricultural Area Utilization; LU = Unit Livestock.

Overall agro-environmental performance reflects the highly specialized nature of oasis date production. Crop diversity is limited and livestock is absent, with perennial date palms occupying nearly the entire utilized agricultural area. Plot management is characterized by medium-sized farms, typically ranging from 2 to 3 ha, with the largest homogeneous production units not exceeding 2 ha. Consequently, indicators related to livestock density and forage management are either non-applicable or marginal.

Fertilization practices rely primarily on organic inputs, complemented by limited legume cultivation for household consumption and low levels of mineral fertilization, mainly sulfur. Pesticide use remains moderate, with plant protection treatments applied to approximately 25–50% of the cultivated area and no veterinary interventions recorded.

Soil and water management practices exhibit partial adoption of conservation measures, including reduced tillage frequency, limited anti-erosion landscaping centered on date palm structures and increasing use of drip irrigation systems supplied predominantly by collective GDA wells. Energy dependence remains moderate, characterized by low fuel consumption, reliance on the national electricity grid and the absence of renewable energy installations. The aggregate score for the agro-environmental dimension is capped at a maximum of 100 points.

2.4.2. Socio-Territorial Sustainability Dimension

The socio-territorial dimension was assessed using six indicators (B1-B6), detailed in Table 3, capturing product quality, market integration, employment, social involvement, training and working conditions. The assessment revealed the following profile across the sampled farms.

Table 3. Socio-territorial sustainability indicators, calculation methods, and scoring criteria for farm operation.

Indicators	Components	Calculation Method	Principal Characteristics of Operations
B1 Product quality	● Production linked to a quality label or local terroir	● Affiliation of one or more products to a quality or regional label (AOC, IGP, etc.): 10	Date palm production
		Production representing more than 10% of turnover: 5	
		● Production in accordance with national organic farming standards: 5	
	● Traceability	Production representing more than 20% of turnover: 3	DN/DC dates
		● Existence of a system or possibility of partial traceability: 2	
		● Existence of a system or possibility of total traceability: 5	
B2 Promotion through short supply chains	● Share of short-supply chain sales	Percentage of production sold through short supply chains:	Direct sale to collectors/exporters
		● Per 20% of turnover: 2; 80% and above: 9	
	● Share of value-added products	Farm products added value (packaging, processing, etc.):	Processes dried dates/common dates, date pits
		● Less than 10% of production: 2	
		● Between 10% and 20% of production: 4	
		● More than 20% of production: 6	
B3 Contribution to employment	● Contribution to employment (CE)	Number of jobs created per hectare: CE = UTH/SAU	Uses casual labor and/or Khamass (1/5)
		● CE greater than 5: 10	
		● CE between 5 and 3: 6	
	● Youth employment (men and women < 35 Years)	● CE less than 3: 4	One man, sometimes two, and in some cases
		● 2 per man and 4 per woman under 35: 10	
B4 Social involvement	● Involvement in associations (professional or other)	● Involvement in a structured association: 4	Members associated with the GDA and UTAP
		● Involvement in several associations: 6	
		● Responsibility in an association: 9	
	● Living on or near the farm	● Home located on the farm: 6	Outside the farm; within a 5 km radius with means of transport
		● Home located near (less than 2 km) the farm: 4	
		● Home far from the farm (more than 2 km): 0	

Table 3. Cont.

Indicators	Components	Calculation Method	Principal Characteristics of Operations
B5 Training and multiple activities	• Level of training or technical knowledge in agriculture	• Education: agricultural techniques or higher education: 4; High school: 3; Middle school: 2; Elementary school: 1	Training based on experience gained
	• Number of training days received annually	• None: 0, Seniority: 1 • Less than 10 days/year: 2 • 10 days/year or more: 4	Several training courses, composting, driving, etc.
	• Practice of other income-generating activities on the farm and participation in the training of third parties	Development of other activities on the farm such as agro-tourism, educational activities (hosting students, interns, or professionals), or socio-agronomic experiments: 2	Hosting students from various agricultural schools and institutes/visitors
B6 Reception and health and safety	• Paths or access to plots	Access roads to the farm and paths leading to the various plots in: • Good condition and regularly maintained: 4 • Poor condition and insufficiently maintained: 2	Paths created by neighbors
	• Quality of reception and accommodation	• Existence of accommodation for workers and visitors: 4 • Quality of accommodation and reception facilities: Average 2; Good: 4	Exists on some farms
	• Quality of production infrastructure and equipment (livestock buildings, irrigation, machinery, etc.)	• Ventilation, lighting, and security of facilities: 4 • Compliance with health and safety standards in practices: 2	Average density greater than 150 p/ha
	• Recycling of non-organic waste	• No recovery/disposal in nature/landfill: 0/burning: −1 • Sorting or recovery of less than 20%: 2 • Sorting or recovery of more than 20%: 4	Valorization of sorting waste for dry flour

Product quality (B1) was primarily linked to date production, with only partial compliance with quality labels, organic standards and traceability systems. Labeled or organic production constituted a limited share of turnover and traceability was generally partial. Promotion through short supply chains (B2) remained moderate, as sales were largely oriented toward collectors or exporters. Value-added activities, such as date drying, processing of common dates, or utilization of date pits, contributed marginally to total production.

Employment contribution (B3) was characterized by a limited number of jobs created per hectare, relying predominantly on casual labor and traditional sharecropping (*khamass*), with low but existing participation of workers under 35 years old. Social involvement (B4) was reflected through membership in professional organizations like the *Groupements de Développement Agricole* (GDAs) and the national farmers' union (UTAP), although responsibilities within these structures were limited. Most farm managers resided outside the farm but within a short commuting distance.

Training and diversification (B5) relied mainly on experiential knowledge, supplemented by occasional technical training sessions. A subset of farms engaged in additional activities such as hosting students or visitors. Finally, reception and health and safety conditions (B6) showed mixed performance, with variable access infrastructure, partial availability of accommodation, average production facilities, incomplete compliance with health and safety standards, and limited but emerging practices for sorting and valorizing non-organic waste.

2.4.3. Economic Sustainability Dimension

The economic sustainability dimension was operationalized through four core indicators (C1–C4), detailed in Table 4. An analysis of the sampled farms revealed key trends in their economic performance.

Table 4. Economic Sustainability indicators, calculation methods, and scoring criteria for farm operation.

Indicators	Components	Calculation Method	Principal Characteristics of Operations
C1—Economic Viability	Global economic viability	Viability economic (VE): GOS = GM/SMAG annual • VE: Less 1 SMAG: 5 • VE: Between 1- 2 SMAG: 10 • VE: From 2 to 3 SMAG: 15 • VE: More than 3 SMAG: 20	GOS less than minimum agricultural wage, depending on the year, price and age of the palm trees
C2—Commercial vulnerability	Share of revenue from the important production (as a percentage of revenue)	The largest production or the main business generates: • Less than 25%: 15 • From 25 to 50%: 10 • More than 50%: 5	Less than 25%
	Share of revenue from the largest client (as a percentage of revenue)	Revenue from the largest client: • Less than 25%: 15 • 25 to 50%: 10 • More than 50%: 5	More than 50%
C3—Financial autonomy	Financial Dependence	Financial Dependence (DF): Total (Debts)/GOS • Less than 20%: 20 • Between 20 and 30%: 15 • Between 30 and 50%: 10 • More than 50%: 0	Between 30 and 50%; depends on the income received on the last year
C4—Efficiency of the production process	Global Efficiency (ESP: Gross Margin/ Production Value)	Global Efficiency = (Production value—Intermediate consumption) /production Value • Less than 25%: 10 • Between 25 and 50%: 20 • More than 50%: 30	Less than 25%

GOS: Gross Operating Surplus; GM = Gross Margin; SMAG = Annual Minimum Agricultural Wage.

Economic viability (C1), measured by the ratio of gross operating surplus to the annual minimum agricultural wage (SMAG), was generally low, with most farms exhibiting values below one SMAG. This reflects limited income stability, influenced by factors such as palm age and market price fluctuations. Commercial vulnerability (C2) analysis showed a pattern of low dependence on a single product but high dependence on a dominant client or buyer. Financial autonomy (C3), assessed via the debt-to-income ratio, indicated a moderate level of financial dependence across farms, largely contingent on income levels from the previous year. Finally, production efficiency (C4), measured by the share of value added in total production value, remained low, suggesting limitations in the efficiency of the production process itself.

3. Results

3.1. Assessment of Sustainability Dimensions by Oasis Type

Table 5 presents the aggregated sustainability scores for modern and traditional oases across the three dimensions. Overall, modern oases achieved a marginally higher composite sustainability score (57%) compared to traditional oases (54%).

Table 5. Sustainability scores by oasis type.

Dimension	Component	Indicator	Modern Oases		Traditional Oases		Max. Pos.
			Score	Score %	Score	Score %	
Agro-environmental	Diversity	A1—Crop diversity	18	100.0	18	100.0	18
		A2—Animal diversity	0	0.0	2	20.0	10
	Spatial organization	A3—Plot management	10	83.3	12	100.0	12
		A4—Livestock density and forage management	8	80.0	8	80.0	10
	Agricultural practices	A5—Fertilization and organic-matter management	6	33.3	8	44.4	18
		A6—Use of pesticides and veterinary products	6	60.0	10	100.0	10
		A7—Soil and water management	7	43.8	7	43.8	16
		A8—Energy dependence	5	83.3	3	50.0	6
Total agro-environmental score			60	60.0	68	68.0	100
Overall agro-environmental score (all oases)			64		64%		
Socio-territorial	Product quality and promotion of local produce	B1—Product quality	15	75.0	15	75.0	20
		B2—Promotion through short supply chains	15	100.0	13	86.7	15
	Employment and services	B3—Contribution to employment	6	30.0	7	35.0	20
		B4—Social involvement	6	40.0	8	53.3	15
	Ethics and human development	B5—Training and multiple activities	7	70.0	7	70.0	10
		B6—Reception and health and safety	8	40.0	10	50.0	20
Total socio-territorial score			57	57.0	60	60.0	100
Overall socio-territorial score (all oases)			58.5		58.5%		
Economic	Viability	C1—Economic viability	10	50.0	5	25.0	20
		C2—Commercial vulnerability	15	50.0	10	33.3	30
	Independence	C3—Financial autonomy	10	50.0	10	50.0	20
	Efficiency	C4—Efficiency of the production process	20	66.7	10	33.3	30
Total economic dimension score			55	55.0	35	35.0	100
Overall economic score (all oases)			45		45%		
Total sustainability score			172	57%	163	54%	300
Overall sustainability score *			167.5		55%		

* Overall sustainability score is calculated as the sum of the average of the three dimensions' scores.

A disaggregated analysis reveals distinct performance patterns. In the agro-environmental dimension, both systems demonstrated moderate performance, with traditional oases scoring higher (68%) than modern oases (64%). Traditional systems exhibited superior results in crop/animal diversity and pesticide management, reflecting more diversified and ecologically integrated practices. Conversely, modern oases performed better in energy efficiency and land management.

In the socio-territorial dimension, scores were comparable, with traditional oases at 60% and modern oases at 57%. Traditional systems were distinguished by stronger social embeddedness and local product promotion, while modern oases showed a slight advantage in access to training and safety protocols.

This economic advantage reflects scale effects, market integration and production specialization inherent to modern oasis systems. A pronounced divergence was observed in the economic dimension, where modern oases scored substantially higher (55%) than traditional ones (35%). Modern systems demonstrated greater production efficiency and financial autonomy, indicating stronger economic viability and resilience.

Overall, these findings underscore a clear trade-off: modern oases exhibit greater economic sustainability, whereas traditional oases maintain relative advantages in agro-environmental and socio-territorial performance, highlighting the distinct and complementary profiles of the two systems.

The survey encompassed farms across all sampled oases, each of which engaged in date production. Application of the IDEA method yielded an average overall farm sustainability score of 152 points.

Based on the aggregate IDEA scores, oasis agriculture in the study region demonstrates an intermediate level of sustainability, with an average composite score of 55%. A disaggregated analysis, however, reveals notable variation across the three sustainability dimensions and between oasis typologies.

The economic dimension recorded the lowest average score (45), identifying it as the primary constraint to overall sustainability. This was followed by the socio-territorial (58.5) and agro-environmental (64) dimensions. Further differentiation between oasis types is presented in Table 5. Socio-territorial performance showed limited variation between oasis types, with scores of 57 for modern oases and 60 for traditional oases. Agro-environmental scores ranged from 60 (modern) to 68 (traditional), while economic scores ranged from 35 (traditional) to 55 (modern).

Table 6 presents the results of the ANOVA test examining differences in measured parameters between traditional and modern oasis systems. This analysis identifies the indicators with statistically significant contrasts, providing a robust foundation for comparing the two production systems.

Table 6. ANOVA results testing for differences between traditional and modern oasis systems across selected parameters.

Dimension	Variable		Sum of Squares	ddl	Mean Squares	F	Significance
Social characteristics	Gender	Inter-group	0	1	0.102	3.343	0.072
		Intra-group	2	60	0.031		
		Total	2	60			
	Instruction level	Inter-group	6	1	5.848	6.83	0.014 **
		Intra-group	23	27	0.856		
		Total	29	28			
	Involvement in society	Inter-group	1	1	1.123	4.822	0.032 *
		Intra-group	14	60	0.233		
		Total	15	60			
	Staff tenure	Inter-group	691	1	691.276	4.317	0.042 *
		Intra-group	9608	60	160.135		
		Total	10.299	60			
	Age	Inter-group	8	1	7.986	0.083	0.775
		Intra-group	5807	60	96.781		
		Total	5815	61			

Table 6. Cont.

Dimension	Variable		Sum of Squares	ddl	Mean Squares	F	Significance
Agronomic characteristics	Agronomic Diversity (Dc. DN)	Inter-group	23.821	1	23,821.056	5.02	0.029 *
		Intra-group	279.972	59	4745.282		
		Total	303.793	60			
	Production of Other Crops	Inter-group	356.595	1	356,594.792	0.549	0.463
		Intra-group	25,330.966	39	649,511.953		
		Total	25,687.561	40			
	Farm Size	Inter-group	35	1	34.564	18.738	0.001 **
		Intra-group	111	60	1.845		
		Total	145	60			
	Diversity	Inter-group	288,395.926	1	288,395.926	7.778	0.007 **
		Intra-group	2,224,638.268	60	37,077,304.46		
		Total	2,513,034.194	60			
Economic characteristics	Viability	Inter-group	0	1	0.072	0.232	0.632
		Intra-group	19	60	0.312		
		Total	19	60			
	Used Inputs (Costs)	Inter-group	131,992.150	1	131,992,150.4	5.039	0.029 *
		Intra-group	1,545,437.043	59	26,193,848.19		
		Total	1,677,429.193	60			
	Efficiency	Inter-group	280,962.263	1	280,962.263	5.197	0.026 *
		Intra-group	3,189,794.130	59	54,064,307.3		
		Total	3,470,756.393	60			

* significant at 5%; ** significant at 1%.

The ANOVA results (Table 5) reveal significant differences between traditional and modern oasis systems across several social, agronomic, and economic parameters.

Social characteristics show statistically significant differences for farmer education level ($p = 0.014$), involvement in community organizations ($p = 0.032$) and staff tenure ($p = 0.042$). In contrast, farmer age ($p = 0.775$) and gender distribution ($p = 0.072$) did not differ significantly between the two systems.

Agronomic characteristics present marked contrasts. Significant differences were found for agronomic diversity ($p = 0.029$), overall diversity ($p = 0.007$) and, most notably, farm size ($p = 0.001$). The production of other (non-date) crops did not differ significantly ($p = 0.463$).

From an economic perspective, input costs ($p = 0.029$) and production efficiency ($p = 0.026$) varied significantly between traditional and modern systems. However, the indicator for overall economic viability ($p = 0.632$) did not show a statistically significant difference.

Overall, these results indicate that the systemic distinction between traditional and modern oasis systems is driven primarily by differences in farmers' education and experience, structural and functional farm diversity, and the efficiency and cost structure of production, rather than by demographic factors like gender or the immediate measure of economic viability.

The pronounced economic vulnerability of traditional systems, scoring 20 points below their modern counterparts, contrasted with their relatively stronger environmental and social performance. This pattern of a sustainability trade-off, in which no single system type excels across all three dimensions, constitutes the central empirical finding of this study and aligns with observations reported for similar Saharan agroecosystems [22].

3.2. Agro-Environmental Sustainability

Analysis of agro-environmental indicators reveals that sustainability is more strongly maintained in traditional oases than in modern ones (Figure 1).

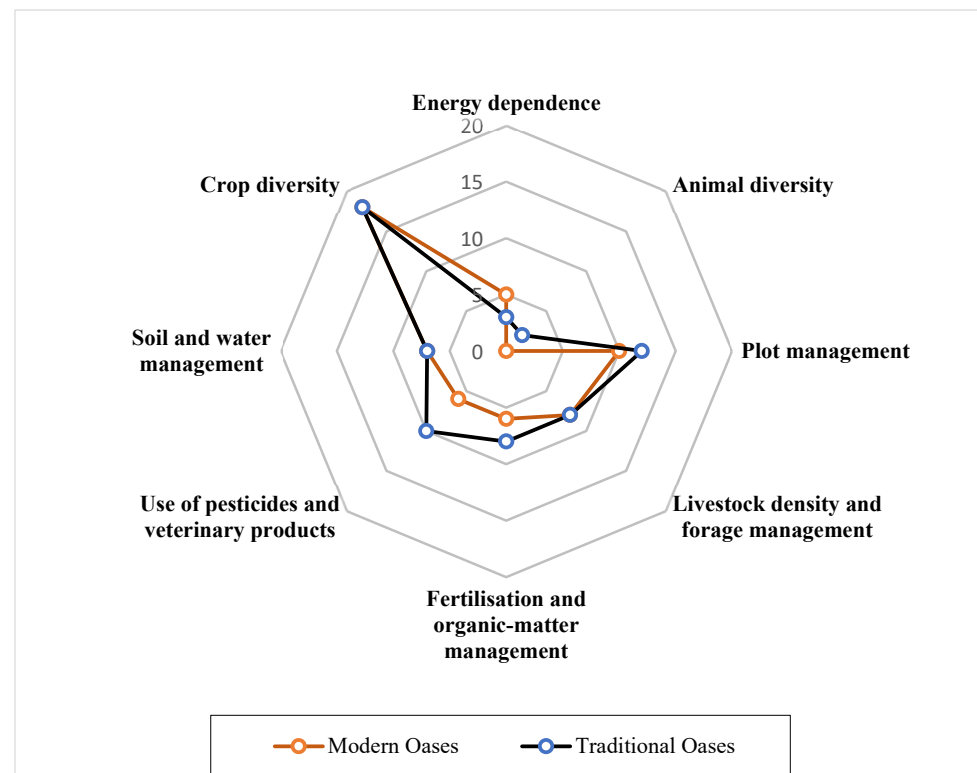


Figure 1. Agro-environmental sustainability scores by oasis type.

This is particularly evident in the superior performance of traditional systems in preserv-ing biodiversity (indicators A1, A2) and minimizing pesticide use (A6), a practice poten-tially influenced by the high cost of such inputs in smaller-scale systems.

Modern oases, while only weakly mechanized, exhibited a relatively higher degree of energy dependence (A8). The overall agro-environmental scores, suggest that date palm cultivation in both systems does not present a predominant concern regarding contribu-tions to global warming, nor does the low mechanization level markedly elevate energy dependence. Deficits were observed across both systems in several key areas, including soil fertility management (mineral balance, A5), herbicide and pesticide application (A6), soil and water conservation practices (A7), and crop rotation.

Notably, modern oases demonstrated better performance in specific resource man-agement practices, such as the application of larger quantities of organic matter (A5), more efficient plot management (A3), and the adoption of advanced water management tech-niques (A7). This suggests that irrigation methodology is a key determinant of water productivity, a finding consistent with other studies in arid oasis contexts [23]. Conversely, the multi-layered structure and diversified practices of traditional oases align more closely with broad agroecological principles, supporting conclusions regarding their role in main-taining ecological integrity [24].

This contrast underscores a distinct trade-off within the agro-environmental dimen-sion: modern oases optimize certain efficiency-focused management practices, while tradi-tional systems excel in maintaining broader ecological integrity and diversity.

3.3. Socio-Territorial Sustainability

The comparative performance across socio-territorial indicators reveals differentiated profiles for modern and traditional oasis farms (Figure 2). While modern farms achieved a marginally higher overall score, each system exhibited distinct strengths.

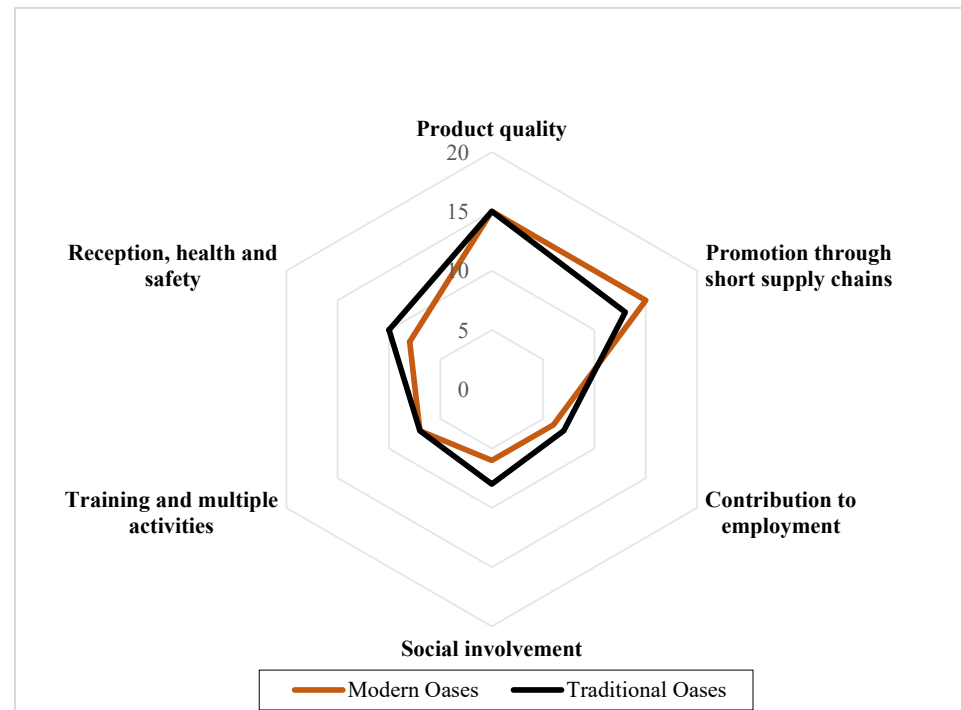


Figure 2. Socio-territorial sustainability scores by oasis type.

Modern farms demonstrated a clear advantage in promotion through short supply chains (B2), indicating stronger and more direct market integration. Conversely, traditional farms outperformed modern ones in several community-focused areas: product reception and health and safety standards (B6), social involvement (B4), and contribution to local employment (B3).

In the domains of training and skills development (B5) and product quality (B1), the performance of both systems was comparable, with traditional farms remaining competitive.

In summary, these findings suggest a distinct socio-territorial dichotomy. Modern farms are oriented toward market efficiency and commercial quality assurance, leveraging their scale and specialization. Traditional farms, in contrast, exhibit deeper social embeddedness and a stronger role in sustaining local employment and community welfare, consistent with their historical and cultural role within oasis societies. Both systems, however, maintain similar baseline levels of investment in human capital and adherence to fundamental product standards.

3.4. Economic Sustainability

An analysis of the three sustainability pillars confirms the economic dimension as the most constrained, with significantly lower scores relative to agro-environmental and socio-territorial performance. As illustrated in Figure 3, a pronounced divergence exists between oasis types: modern farms consistently outperformed traditional ones across most economic indicators.

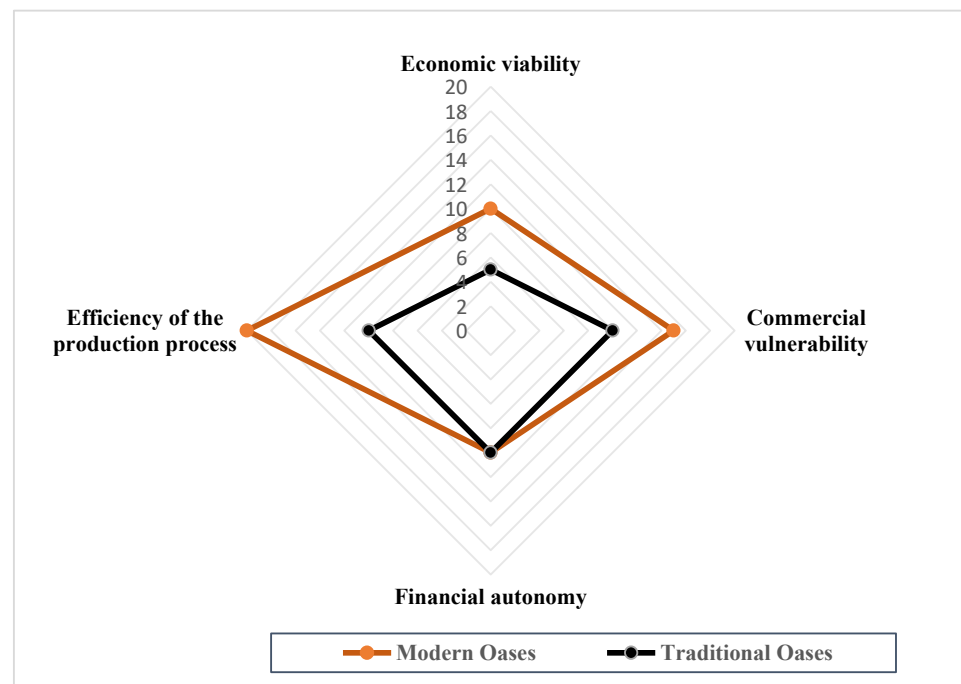


Figure 3. Economic sustainability scores by oasis type.

Modern oasis farms demonstrated superior economic viability (C1), production efficiency (C4), and resilience to commercial vulnerability (C2). The sole indicator where performance was broadly comparable was financial autonomy (C3), though modern oases maintained a slight edge.

In summary, modern farms exhibit greater overall economic robustness, characterized by higher operational efficiency and market resilience. Traditional farms, while demonstrating stability, operate at a lower level of economic efficiency and are more vulnerable to market shocks. This consistent pattern of modern outperformance underscores a systemic economic divergence rooted in the fundamental structural and managerial differences between the two models.

4. Discussion

Understanding the relationship between farm sustainability and oasis typology is critical for formulating effective agricultural strategies and policies in Tunisia, particularly for high-value crops such as date palm [25,26]. This study contributes to the growing body of literature on sustainability assessment in Mediterranean agriculture by moving beyond descriptive scoring toward a diagnostic interpretation of systemic trade-offs. Unlike prior applications of IDEA in Tunisia, which largely focused on dairy, olive, or irrigated cereal systems, this work explicitly links sustainability outcomes to structural typologies and examines the mediating role of farm scale. In doing so, it provides both methodological and empirical contributions to the design of context-sensitive sustainability policies.

The results provide clear support for H1 and H2. As hypothesized, the three sustainability dimensions responded differentially to oasis typology (H1). The agro-environmental and socio-territorial dimensions exhibited relatively balanced performance between systems, while the economic dimension revealed pronounced disparities (Table 6). This confirms that the structural and managerial characteristics defining each oasis type have distinct impacts on different facets of sustainability. Hypothesis 2 (H2) is strongly supported by the significantly higher economic dimension scores of modern oases (55% vs. 35%), confirming their greater economic robustness, efficiency and resilience to commercial vulnerability.

Regarding H3, the results are suggestive but not conclusive. ANOVA confirmed that modern oases operate at significantly larger scales than traditional systems ($p < 0.001$, Table 6), and modern oases also achieved higher economic sustainability scores. This pattern is consistent with the hypothesis that larger farm size may confer economic advantages, but the current study design does not permit a direct test of the relationship between farm size and sustainability scores at the individual farm level. Farm size is confounded with oasis typology, and without multivariate analysis, its independent effect cannot be isolated. Thus, H3 is considered partially supported and warrants further investigation using regression-based approaches.

Overall sustainability scores ranged from 152 to 157 points, aligning with findings from prior studies on Tunisian agricultural systems [14–16]. The results confirm significant variability in sustainability performance across oasis types, substantiating H1. Specifically, larger farms, predominantly associated with modern oasis systems, demonstrated higher operational efficiency and superior resource optimization. In contrast, smaller farms within traditional oases maintained greater agroecological diversity but displayed lower economic resilience. This reflects a fundamental trade-off: modern oases are optimized for market-driven economic performance, while traditional systems excel in maintaining ecological integrity and socio-territorial embeddedness.

The lowest sustainability scores were consistently recorded for the economic dimension in both oasis types, a pattern also identified in other Saharan agroecosystems [22,27]. This contrasts with findings from northern Tunisia, where Attia et al. [13] identified the socio-territorial dimension as the primary constraint for dairy farms. In our study, the economic dimension emerges as the principal challenge for date farms. The relatively higher performance in socio-territorial indicators aligns with [13] and may be attributed to farmers' favorable educational attainment and robust integration into local social networks [14].

The economic challenges identified underscore systemic structural and institutional constraints within the sector. In Tunisia, factors such as market concentration, fragmented value chains, and limited on-farm diversification collectively constrain farm profitability. Enhancing producer income must therefore be a strategic priority. Potential pathways include providing targeted financial support [17], facilitating controlled modernization, developing improved marketing channels, and aligning local pricing more closely with international standards for premium varieties like Deglet Nour.

Notably, the limited variability in economic performance across farm sizes within each system contrasts with the high variability reported among dairy farms by M'Hamdi et al. [14]. In the context of Tunisian date production, this homogeneity may be attributed to the significant role of state-regulated market mechanisms and standardized export channels, which attenuate income differentiation.

The findings demonstrate that sustainability performance in Tunisian oasis systems is closely linked to oasis typology, reflecting two distinct development models. Traditional oases exhibit stronger agro-environmental sustainability, consistent with agro-ecological principles such as crop diversification, reduced input use, and ecological resilience in water-scarce environments. In contrast, modern oases achieve higher economic performance due to specialization, larger farm size, and stronger integration into export-oriented value chains. This trade-off highlights a broader sustainability transition dynamic, where market-driven intensification improves economic outcomes but may weaken ecological multifunctionality.

Moreover, the economic vulnerability of traditional systems appears structurally linked to market concentration and unequal access to capital rather than technical inefficiency alone, underscoring the political economy dimension of oasis development. This raises a critical question: why do traditional systems, which deliver public goods (biodiversity, landscape heritage, local food security), receive no commensurate public support?

Addressing this imbalance will require not only technical solutions but also institutional reforms that recognize and remunerate the non-market contributions of smallholder farmers.

The sustainability trade-off identified in this study reflects a broader tension observed in agricultural systems undergoing modernization under conditions of aridity and market integration. From a sustainability transitions perspective, modern oases exemplify a path of specialization and standardization, driven by export-oriented value chains and state-led development programs. Traditional oases, by contrast, represent a multifunctional model, wherein ecological diversity and social reproduction are prioritized over short-term economic optimization. This duality is not unique to Tunisia; similar dynamics have been documented in Moroccan oases, Spanish Mediterranean agroecosystems, and Saharan date-producing regions more broadly.

5. Limitations and Future Research

While the IDEA method proved to be an effective diagnostic tool, its partial reliance on semi-qualitative indicators and farmer-reported data constitutes a limitation and highlights an opportunity for methodological enhancement. Integrating quantitative biophysical metrics (e.g., water salinity, soil organic carbon) and advanced statistical techniques, such as multivariate regression or structural equation modeling, could strengthen the robustness of future findings and better elucidate the causal relationships among sustainability determinants. Furthermore, the cross-sectional design provides only a temporal snapshot; longitudinal studies are needed to assess trends and resilience to shocks such as drought or price volatility. Finally, while the core finding of a sustainability trade-off is likely transferable to similar arid-land perennial systems, expanding the research to encompass a wider range of oasis regions and farm scales would enhance the generalizability of the conclusions.

Regarding Hypothesis 3, which proposed a positive relationship between farm size and sustainability, this association was inferred from the significant size differential between oasis types and their respective economic scores. Due to the categorical structure of the typology and the absence of continuous regression modeling, we cannot confirm whether farm size exerts an independent effect or is merely collinear with other modern oasis attributes (e.g., market integration, capital intensity). Future studies should employ multivariate techniques, such as multiple linear regression or structural equation modeling, to disentangle these effects and isolate the specific contribution of scale from other confounding factors.

6. Conclusions

This study evaluated and compared the sustainability of date palm farms in the contrasting modern and traditional oasis systems of southern Tunisia using the IDEA assessment framework. The analysis yielded clear findings with direct implications for policy and management.

The results confirm that oasis type is a primary determinant of sustainability performance, revealing a systemic trade-off. Modern oases exhibit greater economic robustness (supporting H2), characterized by higher efficiency and market resilience. In contrast, traditional oases maintain stronger agro-ecological integrity and socio-territorial embeddedness (supporting H1). Furthermore, the results indicate that modern oases, which are significantly larger on average ($p < 0.001$), exhibit higher economic sustainability scores. While this suggests a potential positive association between farm size and economic performance, the cross-sectional design and limited sample size preclude a direct causal or correlational test at the individual farm level. Further research using multivariate analysis is needed to isolate the specific effect of scale from other confounding factors inherent to oasis typology.

This divergence is not a defect but a diagnostic signal: it reflects two distinct development models, each with specific strengths and vulnerabilities. Consequently, it necessitates targeted, differentiated strategies. For modern oases, policy should focus on mitigating environmental externalities by rationalizing input use, promoting precision agriculture, and adopting soil and water conservation best practices. For traditional oases, priorities include enhancing economic viability by improving market access, diversifying income sources, and facilitating credit for appropriate small-scale technologies.

At the socio-territorial level, strengthening farmer organizations and extension services is crucial for both systems, with particular attention to empowering smallholders and integrating women into the value chain. These findings provide a robust empirical basis for designing differentiated sustainability pathways for oasis agriculture under arid conditions.

Critically, modern and traditional oases are not in competition but fulfill complementary roles within the agricultural landscape and national economy. Modern systems are optimized for productivity and export earnings, while traditional systems are vital for biodiversity conservation, cultural heritage, and local food security. A dual-track policy framework is therefore essential, one that supports the economic modernization and environmental sustainability of modern oases while safeguarding and enhancing the ecological and socio-economic functions of traditional oases. Recognizing and remunerating the non-market public goods provided by traditional systems will be central to any equitable and durable sustainability transition. This integrated approach is key to ensuring the long-term resilience of Tunisia's vital date palm sector.

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