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Evaluating the Impact of Irrigation Water Blending Practices and Quality Enhancement on the Productivity of Date Palm (Phoenix dactyliferous L.) in Wadan, Libya.

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Abstract
This study aimed to evaluate the impact of mixing irrigation water from shallow and deep wells and improving its quality characteristics on the quantitative and qualitative productivity of date palms (Phoenix dactylifera L.) in Waddan, Libya. The study employed a descriptive-analytical approach and a cross-sectional design. Experimental procedures involved collecting representative water samples from 12 groundwater wells (comprising both deep and shallow wells) to analyse physicochemical properties, specifically electrical conductivity (EC), pH, and major dissolved ion concentrations and to calculate chemical indices related to permeability and salinity, such as the Sodium Adsorption Ratio (SAR), the adjusted SAR (SARadj), and Residual Sodium Carbonate (RSC). The field survey steps also included distributing a questionnaire to a simple random sample of 40 farmers to document irrigation methods employed (such as surface irrigation using modern systems), water-mixing practices, and field treatments such as the application of acids and soil amendments.

Hydrochemical results indicate that the water falls within the sodium-sulfate classification, revealing a distinct chemical discrepancy between conventional SAR and SARadj values: the latter exceeds 20 in several wells due to elevated bicarbonate concentrations, suggesting a deterioration in soil permeability and structure. Conversely, all samples recorded negative RSC values (reaching -19.19 meq/L), confirming an abundance of calcium and magnesium, which act as natural soil conditioners. Field observations revealed that surface basin irrigation is the prevailing method and that 95% of farmers encounter clear signs of salinity. While 82.5% of farmers employ water mixing as a strategy to reduce salinity levels, statistical analysis demonstrated a significant relationship ($P=0.011$) between water management and improvements in both the quantity and quality of production. Consequently, the study concludes that there is an urgent need to shift from haphazard mixing practices to systematic, science-based management

It recommends developing a safe mixing model based on periodic laboratory analyses and transitioning to modern irrigation systems to protect the soil from secondary salinisation and ensure the economic and environmental sustainability of the date palm crop in Waddan.

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Introduction

Water constitutes the primary governing and limiting factor for agricultural expansion amidst current climate change dynamics and escalating water stress in arid regions [5]. However, the concept of arable water is no longer restricted to quantitative abundance; it has become intrinsically linked to chemical composition and its long-term impact on soil sustainability and crop health [4]. Water quality is defined by its capacity to maintain the physical and physicochemical properties of the soil, ensuring the prevention of saline or sodic environments that inhibit plant growth or transmit toxic effects through the food chain to humans and livestock [14].

The salinity paradigm emerges as one of the most complex challenges facing crop production, where crops are classified based on their physiological responses into varying categories of salt tolerance [11]. This resistance is not merely a passive survival trait but involves sophisticated mechanisms including osmotic adjustment and ion selectivity enabling plants such as the Date Palm (Phoenix dactylifera L.) to thrive in environments that would otherwise be hostile to other crops [13].

Agriculture in Wadan (central Libya) relies on two hydraulically and chemically distinct water systems [6]. The first system comprises a deep aquifer accessed via artesian wells, characterised by a relatively stable ionic composition [9]. The second system consists of a shallow aquifer fed by farm wells, which is highly sensitive to anthropogenic activities and environmental shifts, rendering it prone to secondary salinisation caused by irrigation water evaporation and subsequent salt accumulation in the root zone [21].

Based on foundational studies in saline water management [22,16], sustaining agricultural productivity depends on rigorous chemical assessment and the implementation of strategic water-blending techniques [24]. In this context, this study seeks to achieve the following scientific and applied objectives:

1- To determine the ionic fingerprint and physicochemical characteristics of both deep and shallow aquifers in the Wadan region, identifying chemical discrepancies between traditional and adjusted indices such as Sodium Adsorption Ratio (SAR), Adjusted (SARadj), and Residual Sodium Carbonate (RSC) to clarify salinity and solute dynamics.
2- To analyse the correlation between the hydrochemical properties of blended irrigation water and the quantitative and qualitative yield efficiency of date palms, thereby establishing the osmotic stress thresholds that induce fruit quality degradation.
3- To construct a science-based model driven by precise hydrochemical parameters to determine optimal blending ratios between deep and shallow well waters, effectively replacing empirical trial-and-error practices with standardised laboratory-guided protocols.
4- To evaluate the efficacy of farmers' field practices and soil conditioner applications as mediating factors, providing actionable scientific recommendations to protect soil against secondary salinisation and ensure the long-term economic sustainability of Wadan's date palm orchards.

Research Problem:

The research problem is centred on the qualitative and quantitative degradation of date palm yields in Wadan, hypothetically attributed to hydrochemical shifts in irrigation water. The problem is manifested in the following:

1-An unstudied gap between the characteristics of deep groundwater and shallow (farm) wells influenced by anthropogenic activities.
2-The lack of identification of specific salinity stress thresholds that lead to the decline in fruit quality.
3-The absence of a scientific basis for water-blending practices among farmers, potentially leading to soil sodium accumulation and diminished productivity.

Significance of the Study:

The intrinsic value of this research lies in its integrated applied nature, linking hydrochemistry, human behaviour, and agricultural output in an arid environment (Wadan). Its significance is highlighted through two main axes:
First: Scientific Significance:
1- Providing a precise and updated physico-chemical characterisation of both shallow and deep aquifers in Wadan, identifying the unique ionic fingerprint of each water source.
2-Developing a science-based Safe Blending Model utilising technical indicators such as the Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC), replacing current trial-and-error practices.
Second: Economic and Production Significance
Enhancing Yield and Quality: By identifying the chemical elements responsible for osmotic stress, which causes fruit stunting and quality degradation, thereby boosting the market value of local dates.
Soil Sustainability Management: Protecting Wadan’s orchards from secondary salinisation caused by unbalanced irrigation water, which reduces the long-term costs of land reclamation.

Research Hypotheses:

Null Hypothesis (H0): There is no significant relationship between the educational level or agricultural experience of Wadan farmers and their implementation of water-blending practices or modern irrigation techniques.
Alternative Hypothesis (H1): There is a positive correlation between the level of awareness regarding salinity risks and the adoption of water-source blending techniques to improve production.

Materials and Methods:

1. Study Area
This study was conducted in the city of Wadan (Al-Jufra District, Libya), a region characterised by an arid environment that relies entirely on groundwater as the primary source for date palm (Phoenix dactylifera L.) irrigation. The study adopted a comparative and direct correlation approach, selecting 12 water sampling points across Wadan.
2. Water Sampling and Physicochemical Analytical Procedures
Four geographically dispersed locations were selected within the study area. Each location comprised one primary deep (artesian) groundwater well and two adjacent shallow farm wells. Operational mechanics at these sites involve extracting water through a piping system and conveying it into primary storage basins, where deep groundwater is blended
with shallow water before irrigation.
Group (A): 4 public deep (artesian) groundwater wells in Wadan.
Group (B): 8 private shallow wells situated on farms adjacent to the deep wells, selected to assess the influence of agricultural practices and aquifer interaction.

Water samples were collected in accordance with standard sampling protocols established by the American Public Health Association (APHA). Samples were gathered in sterile polyethene bottles after purging the wells for 15 minutes to obtain representative aquifer water. The containers were tightly sealed and transported under refrigeration at $4C^0$. Subsequently, the samples were subjected to laboratory analysis following internationally recognised protocols to evaluate their compliance with global standards for irrigation water suitability.

- Hydrogen Power (pH): ISO 10523:2008(E), Electrode method.
- Electrical Conductivity (EC): ISO 7888:1985(E), Electrode method.
- Total Dissolved Solids (TDS): Gravimetric method by evaporation at 180°C (Standard Methods 2540 C).
- Calcium (Ca^{+2}): EDTA Titrimetric Method (Standard Methods 3500-Ca B).
- Magnesium (Mg^{+2}): Titrimetric Method (Standard Methods 3500-Mg B).
- Sodium (Na^{+}): Flame Emission Photometric Method (Standard Methods 3500-Na).
- Potassium (K^{+}): Flame Photometry Method (Standard Methods 3500-K B).
- Carbonates (CO_3^{-2}): Alkalinity Titrimetric Method (Standard Methods 2320 B).
- Bicarbonates (HCO_3^{-}): Alkalinity Titrimetric Method (Standard Methods 2320 B).
- Chloride (Cl^{-}): ISO 9297:1989(E), Mohr's Method.
- Sulphates (SO_4^{-2}): Gravimetric Method with ignition of residue (Standard Methods 4500-SO4).

(1): Classification, Coding, and Geographic Locations (Coordinates) of the Study Wells:-

No.	Well Type	Well Code	Location (Coordinates)	
			Longitude (E)	Latitude (N)
1	The First Primary Groundwater Well	GW-01	016 08°.3209	2910°.2963
2	Adjacent Shallow Well (Farm 1)	SW-01-A	016 08°.5224	2910°.2934
3	Adjacent Shallow Well (Farm 2)	SW-01-B	016 08°.5494	2910°.0493
4	The Second Primary Groundwater Well	GW-02	016 08°.0121	29 09°.1607
5	Adjacent Shallow Well (Farm 3)	SW-02-A	016 08°.4606	29 08°.7123
6	Adjacent Shallow Well (Farm 4)	SW-02-B	016 08°.0948	29 08°.9972
7	The Third Primary Groundwater Well	GW-03	016 09°.8554	29 08°.4625
8	Adjacent Shallow Well (Farm 5)	SW-03-A	016 10°.6514	29 08°.6063
9	Adjacent Shallow Well (Farm 6)	SW-03-B	016 10°.3908	29 07°.8201
10	The Fourth Primary Groundwater Well	GW-04	016 12°.2524	29 06°.8899
11	Adjacent Shallow Well (Farm 7)	SW-04-A	016 13°.4609	29 07°.1287
12	Adjacent Shallow Well (Farm 8)	SW-04-B	016 12°.0019	29 06°.9807

3. Calculation of Hydro chemical Indices

To evaluate salinity, sodcity, and permeability hazards on soil and vegetation, the following hydrochemical indices were calculated using established chemical formulas (with all ionic concentrations expressed in meq/L):

To estimate sodium hazards and the impact of irrigation water on soil permeability, the Sodium Adsorption Ratio (SAR) was calculated. The results were interpreted based on international standards established by the U.S. Salinity Laboratory (USSL), according to the classification by [8]. Water quality was categorised into four classes, ranging from Excellent (SAR < 10) to Unsuitable (SAR > 26).

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \ldots\ldots\ldots\ldots\ldots.(1)$$

Irrigation water quality was evaluated using the Adjusted Sodium Adsorption Ratio (SAR_{adj}), in accordance with the international standards established by the Food and Agriculture Organization (FAO) [14]. Based on these criteria, water samples with values of less than 3 were classified as having no restriction on soil permeability. Values ranging between 3 and 9 were categorized as having slight to moderate impacts, while values exceeding 9 were identified as posing severe risks, leading to acute degradation of soil physical properties and permeability.

$$SAR_{Adj} = SAR\ [1 + (8.4 - pH_c)]\ldots\ldots\ldots\ldots(2)$$

The quality of irrigation water was classified based on the Residual Sodium Carbonate (RSC) values according to the criteria established by [3] The samples were categorized into the following classes

Safe Water: RSC values less than 1.25 meq/L (considered excellent for irrigation purposes).

Marginal Water: RSC values ranging between 1.25 and 2.50 meq/L (require specialized soil management and the addition of amendments).

Unsuitable Water: RSC values exceeding 2.50 meq/L (pose a significant hazard and lead to the formation of sodic soils).

$$RSC=(CO3^{-2}+HCO_3^{-}) - (Ca^{+2}+Mg^{+2})\ \ldots\ldots\ldots(3)$$

The Soluble Sodium Percentage (SSP) was evaluated based on established international standards. A value of 60% is considered the critical threshold for irrigation suitability. Water with an SSP below 60% are classified as suitable for irrigation. Conversely, water exceeding the 60% limit is deemed unsuitable due to its high potential for cation exchange, whereby sodium replaces calcium and magnesium on soil colloids. This process leads to the clogging of soil pores and the subsequent degradation of soil permeability to both water and air [25].

$$SSP = \frac{Na}{(\ Ca + Mg + Na)} * 100 \ldots\ldots\ldots\ldots\ldots..(4)$$

The Permeability Index (PI) was applied according to [2] to determine irrigation water suitability levels. This index categorizes water samples into three distinct classes, highlighting the relationship between ionic content and the soil's capacity for water transmission.

Class I (> 75%): Representing maximum permeability; water in this class is considered highly suitable for irrigation.

Class II (25%–75%): Indicating moderate permeability; water is considered marginally suitable and requires careful management.

Class III (< 25%): Representing low permeability; water in this category is classified as unsuitable due to its adverse effects on soil physical structure.

$$PI = \frac{\mathrm{Na + K} + \sqrt{\mathrm{HCO3}}}{(\mathrm{Ca + Mg + Na + K})} * 100 \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The classification of irrigation water quality based on Sodium Percentage (Na%) primarily follows the criteria established by [15]. Water quality is categorized into five distinct levels according to its suitability for irrigation:

Excellent: Na% is less than 20%.

Good: Na% ranges between 20% and 40%.

Permissible: Na% ranges between 40% and 60%.

Doubtful: Na% ranges between 60% and 80%.

Unsuitable: Na% exceeds 80%.

$$\mathrm{Na\%} = \frac{\mathrm{Na^{+} + K^{+}}}{(\mathrm{Ca^{2} + Mg^{2} + Na^{+} + k^{+}})} \times 100 \ldots\ldots\ldots\ldots\ldots (6)$$

According to the classifications of the United States Salinity Laboratory (USSL) and the Food and Agriculture Organization (FAO), the Exchangeable Sodium Percentage (ESP) levels were utilized to determine the extent of soil permeability degradation based on the following thresholds [8]:

- Safe Water (Low Risk): ESP below 6%. At this level, there is no anticipated threat to soil structure.
- Moderate Risk: ESP ranges between 6% and 9%. This level necessitates continuous monitoring of soil permeability.
- Hazardous Water: ESP ranges between 10% and 15%. In this range, soil particles begin to disperse, leading to the clogging of pore spaces.
- Severe Risk: ESP exceeds 15%. At this stage, the soil is classified as sodic soil, characterized by a complete loss of water infiltration and aeration capacity due to severe structural collapse.

$$\mathrm{ESP} = \frac{100 \times (-0.0126 + 0.01475 \times \mathrm{SAR})}{1 + (-0.0126 + 0.01475 \times \mathrm{SAR})} \ldots\ldots\ldots\ldots (7)$$

4. Socio-Agricultural Survey:

The study population comprises all farmers in Waddan, Libya, a region fundamentally dependent on the cultivation of date palm (*Phoenix dactylifera* L.) as its primary economic and environmental pillar. While various agricultural practices exist, including fruit trees, vegetables, and fodder, these are considered secondary activities compared to date production, which remains the central artisanal and agricultural vocation of the region.

Given the applied objectives of this research, a simple random sample of 40 farmers was selected. The sample was designed to represent the prevailing agricultural practices. A structured questionnaire was distributed to gather data on water sources, observable salinity indicators, water-blending practices, and water quality enhancement methods. This sample serves as the empirical basis for interpreting fluctuations in date palm productivity and testing the research hypotheses regarding the impact of human interventions in water resource management.

5. Statistical Analysis

Data were statistically processed and analyzed using the Statistical Package for the Social Sciences (IBM SPSS, Version 26.0). The statistical evaluation comprised the following tests:

- One-Way Analysis of Variance (One-Way ANOVA): Conducted to compare water quality parameters among deep artesian wells, shallow farm wells, and blended water samples across the four studied locations.
- Chi-Square Test (χ^2): Employed to evaluate the independence and statistical significance of associations between categorical management variables (such as water-blending strategies and soil conditioner applications) and the observed improvement in date palm yield and fruit quality, evaluated at a significance threshold of $\alpha = 0.05$.
- Spearman's Rank Correlation Coefficient: Utilized to measure the direction and strength of the monotonic relationship between observed salinity stress levels and the qualitative and quantitative degradation of date fruit yield

Results and Discussion:

Table (2): Physicochemical Properties of Deep and Shallow Groundwater Samples in the Study Area.

S.No	Well ID	PH	TDS p.pm	EC Us/cm	Ca^{2+} Meq/l	Mg^{2+} Meq/l	Na^{+} Meq/l	K^{+} Meq/L	CO_3^{2-} Meq/l	CL^{-} Meq/L	Hco_3^{-} Meq/l	So_4^{2-} Meq/l
1	GW-01	6.4	1922	2.85	85	48	454	36	0	337	498	393
2	SW-01-A	6.9	2558	3.84	273	32	491	37	0	372	427	988
3	SW-01-B	7.4	3900	6.00	260	125	755	44	0	260	411	1776
4	GW-02	6.5	1890	2.80	85	48	445	36	0	355	490	369
5	SW-02-A	7.1	3272	5.03	290	120	575	39	0	532	625	1195
6	SW-02-B	7.3	2785	4.16	280	140	345	38	0	525	604	946
7	GW-03	6.5	1835	2.82	84	53	345	38	0	325	500	384
8	SW-03-A	7.3	3876	6.03	280	150	759	43	0	535	435	1751
9	SW-03-B	7.2	3470	5.18	260	110	370	43	0	568	635	1105
10	GW-04	6.6	1799	2.8	87	52	460	41	0	350	505	377
11	SW-04-A	7.3	2700	4.03	246	146	350	36	0	497	580	908
12	SW-04-B	7.2	2305	3.44	208	126	299	38	0	462	476	865

Table (3): Calculated Indices for Irrigation Water Quality Classification in the Study Area.

S.no	Well ID	SAR Meq/L^{-1}	SAR adj Meq/L^{-1}	RSC Meq/L^{-1}	SSP %	PI%	Na%	ESP%
1	GW-01	7.76	28.54	-0.02	71.63	80.92	68.44	11.61
2	SW-1-A	7.49	23.64	-9.25	57.85	63.82	55.39	8.92
3	SW-1-B	9.63	31.73	-16.51	59.37	63.18	57.40	11.46
4	GW-02	9.57	27.91	-0.15	71.24	80.57	68.00	11.39
5	SW-02-A	7.17	25.07	-14.08	51.66	57.17	49.68	8.52
6	SW-02-B	4.20	14.72	-15.57	38.54	44.84	36.20	4.71
7	GW-03	7.28	21.28	-0.37	64.91	75.64	60.83	8.67
8	SW-03-A	9.10	30.70	-19.17	56.47	60.16	54.65	10.85
9	SW-03-B	4.85	16.78	-11.60	43.85	50.70	41.05	5.57
10	GW-04	9.64	28.46	-0.33	70.97	79.96	67.43	11.42
11	SW-04-A	4.37	15.13	-14.76	39.94	46.35	37.66	4.93
12	SW-04-B	4.04	13.35	-12.93	40.27	46.83	37.47	4.49

The results indicated that the pH values of the water samples ranged between 6.4 and 7.4, falling within the permissible limits set by the FAO. This range is considered ideal for date palm cultivation in the Waddan region, as it enhances the solubility of micronutrients and facilitates phosphorus uptake. Furthermore, it minimizes the risk of immediate carbonate precipitation within irrigation networks. The stability of pH values near neutrality, despite high bicarbonate levels, improves the efficiency of mineral fertilization (fertigation). Consequently, the hydrogen properties of these waters support osmotic absorption and ionic exchange efficiency within the root zone of the date palms.

Electrical Conductivity (EC) results showed significant variability among the studied wells, with values ranging from 2.80 to 6.03 dS/m. According to Richards' classification, most samples fall under the highly saline category (C4), indicating high osmotic pressure in the soil solution. Despite these elevated values, date palm cultivation in Waddan remains a strategically viable option due to the palms' physiological ability to tolerate salinity up to a threshold of 4 dS/m without a significant decline in yield. The high EC is attributed to the ionic dominance of sulphates and sodium, necessitating a management system based on regular leaching fractions to prevent salt accumulation in the root zone and ensure sustainable productivity and fruit quality.

SAR values in the water samples ranged between 4.04 and 9.75, placing them within the low- to medium-hazard categories (S1 and S2) according to the U.S. Salinity Laboratory classification. This relative increase in SAR in certain wells suggests a tendency for sodium accumulation on the soil exchange complex, which may adversely affect soil permeability and aeration in the long term. However, the synchronization between high SAR and high EC partially mitigates the dispersive effect of sodium on soil particles. The study recommends a water-blending strategy to reduce overall SAR levels, alongside the application of chemical amendments to maintain the ionic balance between sodium and calcium in the root zone.

The SARadj results revealed a fundamental discrepancy compared to traditional SAR values, with values ranging from (7.59 to 20.48). The marked increase in SARadj in wells 1, 4 and 10 is attributed to high bicarbonate concentrations, which stimulate the precipitation of calcium as calcium carbonate, thereby increasing the effective sodium ratio in the soil solution. These findings indicate a real threat to soil structure and permeability in the study area. This necessitates intervention through blending groundwater sources to lower SARadj and adding chemical conditioners, such as agricultural gypsum, to compensate for the calcium lost through precipitation, ensuring a healthy root environment for sustainable growth.

Results for RSC estimation showed that all water samples in the study area recorded negative values ranging from -0.02 to -19.19 meq/l. This indicates that the concentration of divalent cations (calcium and magnesium) significantly exceeds carbonate anions, classifying these waters as completely safe for agricultural use according to FAO standards. The dominance of calcium, reflected in negative RSC values, ensures that calcium remains dissolved in the soil solution, reducing sodcity risks and maintaining soil permeability and physical stability. This positively impacts irrigation efficiency and the sustainability of date palm productivity in Waddan.

The Permeability Index (PI) results showed that the majority of irrigation water in the study area falls within Class II according to Doreen’s classification. This indicates that the water is suitable for irrigation but may lead to a gradual decline in soil permeability over the long term due to interactions between sodium, bicarbonates, and soil clay content. These relatively high PI values are linked to elevated bicarbonate levels in some shallow wells, necessitating the adoption of agricultural practices that enhance soil physical properties, such as adding organic matter and agricultural gypsum, to ensure the continuous infiltration of water and air into the root zone.

The estimated ESP values ranged between 4.45% and 11.56%, which are within the agriculturally safe limits (below 15%) according to international standards for soil sodcity assessment. However, ESP values approaching 12% in some shallow wells suggest a potential for slight physical degradation in the long run, particularly regarding water permeability and the formation of surface crusts. Nevertheless, the sulphatic nature of these waters helps limit the dispersive effect of sodium. The study concludes that the water-blending strategy practised in Waddan keeps ESP values within low ranges, providing an ideal environment for palm growth and protecting the soil structure from physical deterioration.

Practical Framework (Field Study and Statistical Analysis):

This framework aims to transform research questions and theoretical hypotheses into tangible results by analysing field data collected from farmers in Waddan. The practical aspect focuses on verifying the correlation between the hydrochemical characteristics of irrigation water (from both deep and shallow wells) and the productive efficiency of date palms.

Table (4): Distribution of the Study Sample According to Primary Crop Types.

Crop Type	Frequency	Percentage(%)
Date Palm	40	100.0
Fruit Trees	0	0.0
Vegetables	0	0.0
Forage Crops	0	0.0
Total	40	100.0

Table (4) exhibits an absolute homogeneity of 100% regarding crop type, with all respondents focusing exclusively on Date Palm (Phoenix dactyliferous L.) cultivation.

The total absence of alternative agricultural options (such as fruit, vegetables, or fodder) indicates that the agricultural system in Waddan is a monoculture. This is primarily attributed to the fact that the date palm serves as the fundamental economic and environmental backbone of the city, being the only crop capable of thriving under the region's specific hydrochemical conditions.

Table (5): Distribution of the Study Sample According to the Applied Irrigation System.

Irrigation System	Frequency	Percentage(%)
Drip Irrigation	40	100.0
Flood Irrigation	0	0.0
Sprinkler Irrigation	0	0.0
Total	40	100.0

The results indicate that 100% of the sampled farmers rely exclusively on modern drip irrigation systems. The complete absence of flood and sprinkler irrigation serves as a highly positive indicator, reflecting the profound awareness among Waddan’s farmers regarding water conservation and the necessity of rationalisation within an arid environment.

Table (6): Distribution of the Study Sample According to Total Farm Area (in Hectares).

Area Hectares	Frequency	Percentage(%)
1 Hectare	1	2.5
2 Hectares	4	10.0
3 Hectares	13	32.5
4 Hectares	22	55.0
Total	40	100.0

In contrast to the previous parameters, the results reveal significant statistical variance in farm sizes among the study sample.

The vast majority of farms (87.5%) fall within the relatively large-scale category (3 to 4 hectares). Specifically, the 4-hectare area represents the largest share at 55%.

Small areas (1 hectare) constitute a negligible percentage of only 2.5%. This indicates that agricultural activity in Waddan is primarily a wide-scale productive venture rather than limited subsistence or domestic farming

Table (7): Distribution of the Study Sample According to Available Water Sources:

Water Source	Frequency	Percentage(%)
Category A	1	2.5
Category B	39	97.5
Total	40	100.0

The results indicate an absolute dominance of shallow wells as the primary water source, accounting for more than 97% of total reliance.

The data reveal a high level of concentration (low variance) in the dependency on the shallow aquifer. From a statistical and hydrogeological perspective, this concentration represents a critical point.

Table (8): Monitoring Salinity Indicators (White Salt Crusts) on Soil Surface and Crops.

Observation of Salinity Signs	Frequency	Percentage(%)
Yes	23	57.5
No	2	5.0
Sometimes	15	37.5
Total	40	100.0

The results in this table reveal a significant salinity crisis within the study area, where 57.5% of the farmers confirmed the presence of permanent salinity indicators, while 37.5% observed them intermittently.

Table (9) Practices of Blending Irrigation Water from Two Different Sources.

Do you practice water blending?	Frequency	Percentage(%)
Yes	33	82.5
No	7	17.5
Total	40	100.0

The results demonstrate that the vast majority of farmers (82.5%) adopt the blending strategy as a primary adaptive mechanism.

This high frequency confirms that blending is the prevailing practice in Waddan. Consequently, investigating the impacts of these practices is the core objective of this research and represents a stringent necessity rather than a mere theoretical inquiry. This widespread adoption justifies the urgent need for standardized protocols to manage the process.

The small percentage of farmers who do not practice blending (17.5%) may be attributed to farms that possess deep wells with relatively stable water quality or farms that are still in the initial stages of soil salinization, where the need for mixing has not yet become critical.

Table (10): Primary Purpose for Practicing Water Blending among the Study Sample.

Purpose of Water Blending	Frequency	Percentage(%)
Salinity reduction	27	67.5
Compensating for water quantity shortage	7	17.5
Reducing groundwater pumping expenditures	6	15.0
Total	40	100.0

This table serves as the primary catalyst for the research hypotheses, as salinity reduction emerged as the leading motivation at 67.5%. These results demonstrate that farmers in Waddan possess an intuitive awareness of salinity hazards and actively attempt to mitigate these risks through technical interventions, specifically blending. However, this awareness of the threat is contrasted by procedural randomness in execution (as will be demonstrated in subsequent tables regarding the determination of blending ratios).

Table (11): Criteria for Determining Irrigation Water Blending Ratios Among the Study Sample.

Methods for Determining Blending Ratios	Frequency	Percentage(%)
Based on laboratory analyses	1	2.5
Based on personal experience and observation	15	37.5
Randomly	24	60.0
Total	40	100.0

The results presented in this table serve as a statistical embodiment of the Arbitrary Management problem outlined in the study's theoretical framework. It is observed that 60% of the farmers practice blending randomly, followed by 37.5% who rely on personal experience and observation. This indicates that a staggering 97.5% of the sample manage irrigation water without adhering to precise hydrochemical standards.

The negligible percentage (2.5%) of farmers who rely on laboratory analysis clearly explains why blending occasionally yields counterproductive results. Without laboratory determination of the Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC), the blending process transitions from a technical solution into a chemical risk. Such uncelebrated mixing may lead to an imbalance in the ionic composition of the water, ultimately causing excessive sodium accumulation and the deterioration of soil structure.

Table (12): Utilization of Water Treatment Technologies Prior to the Irrigation Process.

Adoption of Treatment Techniques	Frequency	Percentage(%)
Yes	9	22.5
No	31	77.5
Total	40	100.0

The results reveal a significant decline in the adoption of water treatment technologies; more than two-thirds of respondents (77.5%) do not utilise any treatment techniques (such as magnetisation, filtration, or sedimentation) before irrigation.

This indicator reinforces the Salt Stress hypothesis. Relying solely on water blending without integrated chemical or physical treatment leaves the crop directly vulnerable to ionic toxicity. Without treatment to mitigate the reactive nature of the blended water, the physiological impact on the date palm remains severe.

Table (13): Usage of Soil Amendments and Acids for Adjusting Water Alkalinity.

Application of Soil Amendments and Acids	Frequency	Percentage(%)
Yes	25	62.5
No	14	35.0
Missing	1	2.5

In contrast to the low adoption of technical treatment systems, the results indicate a significant trend toward the use of chemical amendments, with an adoption rate of 62.5%. This finding suggests that farmers in Waddan prefer additive chemical solutions (such as sulfuric or phosphoric acid) over structural technical solutions (such as installing magnetization or filtration units). This preference likely stems from the lower initial cost and ease of application compared to technical infrastructure.

The high utilization of amendments raises a pivotal research question: Are these additions administered in scientifically calibrated doses, or are they part of the procedural randomness identified earlier? If these chemicals are added without laboratory guidance (as indicated by the findings in Table 11), they may lead to a severe imbalance in soil pH (acid-base balance). Such an imbalance can induce nutrient lockout, impairing the uptake of essential minerals and ultimately leading to fruit stunting (reduced size and quality of dates).

Table (14): Evaluation of Crop Productivity Following the Adoption or Optimization of Water Blending Strategies.

Productivity Assessment	Frequency	Percentage(%)
Significant improvement	32	80.0
No change	4	10.0
Decrease in productivity	4	10.0
Total	40	100.0

The results of this table serve as a fundamental indicator of the effectiveness of field interventions conducted by farmers in Waddan, despite the observed procedural randomness.

A vast majority of farmers (80%) perceive that blending and improvement strategies have led to a significant improvement in productivity. Although 60% of the blending is performed arbitrarily (as shown in Table 11), the significant improvement is scientifically attributed to the dilution of total dissolved solids (TDS) in the shallow irrigation water. This reduces the osmotic stress on the date palms, facilitating better nutrient uptake and fruit development.

The 10% of cases that experienced a decline in productivity represent the dark side of haphazard management; ill-considered mixing can sometimes drive the Sodium Adsorption Ratio (SAR) to critical levels, causing soil physical degradation that negatively impacts crop quality. As for the remaining 10%, this may apply to farms where the soil has reached an advanced stage of secondary salinization, such that simple mixing no longer has a tangible effect without major reclamation interventions.

Table (15): Results of Chi-Square Tests for the Relationship Between Blending Methodology and Crop Productivity.

Statistical Test	Value	(df)	Asymp. Sig. (2-sided)
Pearson Chi-Square	13.042^a	4	0.011
Likelihood Ratio	8.756	4	0.067
Linear-by-Linear Association	4.849	1	0.028
Number of Valid Cases	40		

The Chi-Square (\chi^2) value of 13.042 at a significance level of 0.011 indicates a strong and statistically significant association. Since the p-value (0.011) is less than the alpha threshold ($\alpha = 0.05$), we reject the null hypothesis (H_0) and accept the alternative hypothesis (H_1).

This result confirms that the methodology followed by the farmer in water blending is not merely a procedural formality but a determining factor for crop quality and productivity

Table (16): Results of Chi-Square Tests for the Impact of Soil Amendments and Acid Usage on Crop Productivity.

Statistical Test	Value	(df)	Asymp. Sig. (2-sided)
Pearson Chi-Square	0.870^a	2	0.647
Likelihood Ratio	0.844	2	0.656
Linear-by-Linear Association	0.744	1	0.389
Number of Valid Cases	39		

The statistical output of the Chi-Square test yielded a value of 0.870 with a significance level (p-value) of 0.647. Since the significance (Sig.) value of 0.647 is substantially higher than the predetermined alpha level ($\alpha = 0.05$), we fail to reject the null hypothesis (H_0) and consequently reject the alternative hypothesis (H_1).

This result indicates that there is no statistically significant relationship between the application of soil amendments and the improvement of crop productivity within the study sample. In other words, farmers who utilised acids and those who did not achieved comparable productivity ratings; thus, the use of chemical amendments did not constitute a statistically distinctive advantage in enhancing the final yield.

Table (17): Spearman's Rho Correlation Coefficient between Observation of Salinity Signs and Productivity Assessment.

Variables	Correlation Statistics	Productivity Assessment	Observation of Salinity Signs
Productivity Assessment	Correlation Coefficient	1.000	0.444^ **
	Sig. 2-tailed	.	0.004
Observation of Salinity Signs	Correlation Coefficient	0.444^ **	1.000
	Sig. 2-tailed	0.004	.

(**)Correlation is significant at the 0.01 level (2-tailed).

The results revealed a significant positive correlation coefficient of (0.444) with a significance level (P-value) of (0.004). Since the Sig. (2-tailed) value is less than 0.01, the null hypothesis (H_0) is rejected, and the alternative hypothesis (H_1) is accepted. While the positive sign of the coefficient might suggest a direct proportional relationship, a closer look at the data coding (where consistent observation of salinity signs is linked to a higher demand for improvement) confirms that salinity is the actual driver behind changes in productivity.

Table (18): Spearman's Correlation Coefficient Between Irrigation Scheduling and Productivity Evaluation.

Variables	Correlation Statistics	Productivity Assessment	Irrigation Schedule / System
Productivity Assessment	Correlation Coefficient	1.000	0.051
	Sig. 2-tailed	.	0.755
Irrigation Schedule / System	Correlation Coefficient	0.051	1.000
	Sig. 2-tailed	0.755	

The correlation coefficient was 0.051 with a significance level (p-value) of 0.755. Since the significance (Sig.) value is substantially higher than the alpha threshold ($\alpha = 0.05$),we fail to reject the null hypothesis (H_0) and consequently reject the alternative hypothesis (H_1).

This result indicates the absence of a statistically significant correlation between irrigation scheduling (timing) and productivity enhancement in this study.

Furthermore, since 100% of the study sample utilizes drip irrigation systems (as established in Table 5), this method inherently minimizes evaporative losses compared to surface irrigation. Consequently, the specific timing of water application (morning vs. evening) becomes a non-significant variable in the final productivity outcome when faced with acute salinity stress.

Conclusion:

This conclusion presents the final findings of the study, which aimed to evaluate the impact of irrigation water blending practices and water quality improvements on date palm productivity in the city of Waddan. By linking the hydrochemical challenges associated with shallow and deep wells to the field practices of 40 farmers, the study identified the gaps hindering the achievement of optimal productivity. This section outlines the key results obtained, followed by practical recommendations aimed at ensuring soil sustainability and protecting the date crop from secondary salinization.

Research Findings

Based on advanced descriptive and inferential statistical analyses, the study yielded the following key findings:

1. The study confirmed that date Palm (*Phoenix dactylifera* L.) serves as the sole strategic crop (100%) in the region, coupled with complete reliance (100%) on drip irrigation systems. This highlights a high baseline awareness among local farmers regarding the imperative of water conservation in hyper-arid environments.
2. Results demonstrated that 95% of farmers observe visible salinity symptoms on both soil and crops (either consistently or intermittently). This high percentage confirms that hydrochemical shifts in shallow irrigation water have reached a critical threshold.
3. Although 82.5% of farmers resort to water blending as a defensive strategy to mitigate salt concentrations, 97.5% of these blending operations are performed empirically or entirely arbitrarily based on personal experience, devoid of rigorous laboratory diagnostics.
4. The Chi-Square test (χ^2, $P = 0.011$) confirmed a statistically significant relationship between the methodology used to establish water blending ratios and yield improvement. Empirical management and personal trial-and-error were linked to productivity bottlenecks and yield declines compared to scientific blending protocols.
5. The study revealed no statistically significant effect regarding the application of agricultural acids and soil conditioners on yield enhancement ($P = 0.647$). This inefficacy is attributed to the application of unstudied, arbitrary dosages without prior quantitative assessment of actual soil and water requirements.
6. Spearman's rank correlation analysis ($P = 0.004$) demonstrated a strong correlation between observed salinity stress and date fruit quality degradation, establishing salinity as the primary governing variable regulating agricultural productivity and food security in the region

Recommendations:

1. **Transition from Arbitrary to Laboratory-Based Management**: It is imperative for farmers to conduct periodic analyses of both shallow and deep well water to determine Total Dissolved Solids (TDS/EC) and Sodium Adsorption Ratio (SAR) before initiating any blending operations.

2. **Adoption of Safe Blending Models**: Farmers should be trained in the use of scientific blending equations to achieve the specific salt tolerance thresholds for date palms. This replaces "trial and error" practices that often lead to hazardous sodium accumulation.
3. **Rationalization of Chemical Amendment Usage**: The application of acids (sulfuric or phosphoric) must be strictly contingent upon measuring soil alkalinity (pH). This ensures economic feasibility and prevents ionic imbalances within the root zone.
4. **Activating Agricultural Extension Services in Waddan**: Establish a specialized unit to monitor the quality of groundwater for irrigation and provide updated technical guidance to farmers based on seasonal hydrochemical fluctuations.
5. **Expanding Research on Secondary Salinization**: Future research should focus on the long-term impact of current human practices on the sustainability of the shallow aquifer, aiming to protect palm groves from irreversible soil degradation.

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Data Availability

- Yes ☐
- No ☐√

Authors' Contributions

N.	Author Name and Emai and ORCID link	Study Conception / Idea	Data Collection or Contribution to Data Collection	Contribution to Previous Studies / Literature Review	Study Methodology	Conducting Analyses (Practical Aspect)	Data Analysis	Interpretation and Discussion of Results	Approval of Final Version
1	Ibrahim Hamouda Akhlewit	ibrahim.klwet@ju.edu.ly https://orcid.org/0009-0002-9558-8523	√	√	√	√	√	√	√
2									
3									