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Novel low-cost solution for sustainable irrigation in hyper arid regions: Field evaluation of bottle-based subsurface systems

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ABSTRACT

This study examines innovative irrigation optimization strategies for arid regions by integrating treated wastewater and novel subsurface irrigation techniques. Conducted in Ouargla, Algeria, over a 120-day growing season from December 2023 to March 2024, the research employed onion cultivation as a representative crop (N = 240 plants) to evaluate a hybrid irrigation system combining precision drip irrigation with sand-filled plastic bottles for enhanced water efficiency and natural filtration using a randomized complete block design (RCBD) with four replicates. The experimental design incorporated perforated bottles with 2 mm diameter holes, geotextile fabric wrapping, and local dune sand filling to create an effective subsurface water delivery and treatment system. Irrigation scheduling was optimized by comparing theoretical water requirements calculated using CROPWAT software with experimental soil moisture measurements. Results demonstrated that the sand-bottle system achieved water use efficiency (1.42 ± 0.06 kg/m³) statistically equivalent to freshwater irrigation (1.51 ± 0.08 kg/m³) using TOST equivalence testing with ± 10% margin showing strong correlation with theoretical predictions while consuming 23% less water than conventional drip irrigation with treated wastewater (240 ± 18 mm vs 310 ± 15 mm). The sand filtration component effectively reduced biological oxygen demand by 25.3 on average, chemical oxygen demand by 7.76–29.3%, and suspended solids by 57.71–66.44%. However, electrical conductivity increased marginally (5–9.5%) due to salt leaching from sand particles. The system demonstrates sustainable irrigation potential for water-scarce environments, though monthly sand replacement is required to maintain optimal filtration performance.

Keywords: subsurface drip irrigation, treated wastewater reuse, arid agriculture, water use efficiency, sand filtration, low-cost irrigation technology

INTRODUCTION

Arid and semi-arid regions worldwide face unprecedented challenges in sustainable agricultural water management, driven by extreme climatic conditions characterized by elevated temperatures, rainfall variability, and relatively high evaporation rates (Al-Khreisat et al. 2025; Remini, 2021). Due to limited rainfall in arid regions, agricultural productivity is highly dependent on irrigation, this will likely increase due to more extreme drought events in the region (Al-Bakri and Al-Kilani 2025; Al-Kilani et al., 2025; 2024a). With agriculture consuming approximately 70% of global freshwater resources, the imperative for innovative water conservation technologies becomes increasingly critical, particularly in water-scarce environments (Zegait et al., 2025; FAO, 2011). Various solutions have been explored to reduce the pressure on freshwater resources, including improved monitoring technology systems for water management (Al-Omoush et al., 2025; Guenouche al., 2024). Additionally, sensor-based irrigation systems have been explored to conserve irrigation water by supplying the needed crop water requirement and avoid excessive irrigation (Al-Kilani et al., 2024b; Abdelal et al., 2025). These systems are associated with technical complexities and cost considerations, but can be necessary under water-scarce conditions (Abdelal and Al-Kilani, 2024). Hydroponic systems have been shown to reduce water consumption very effectively, but are associated with high investment and operating costs (Abdelal et al., 2024). Other traditional solutions that have been explored also include water harvesting, shifting to drought tolerant crops, and improving soil moisture conservation (Al-Kilani, 2024). Amongst these options, treated wastewater reuse has been identified as a strategic approach to reduce the pressure on freshwater resources. This due to the already existing necessity to handle the wastewater produced from the increasing population growth and industrial activities (Al-Hazmi et al., 2023; Bani-Melhem and Al-Kilani, 2023). The strategic reuse of treated wastewater emerges as a compelling solution for addressing the dual challenges of water scarcity and environmental stewardship associated with wastewater disposal (Al-Kilani and Bani-Melhem, 2025; Mekonnen and Hoekstra, 2016). Treated wastewater can reduce the pressure on freshwater resources and the reliance on chemical fertilizers due to its nutrient content, it can also reduce the risk of groundwater and surface water contamination (Al-Kilani, 2024; Al-Hazmi et al., 2023). Furthermore, it can be much less costly in terms of investment and operating costs compared to other options like desalination (Bani-Melhem et al., 2023a, b). Comprehensive research has demonstrated that crops irrigated with appropriately treated wastewater can achieve yields equivalent to those using freshwater resources, thereby validating the agronomic and economic viability of this approach (Al-Lahham et al., 2003). A comprehensive review by Hashem and Qi (2021) highlighted significant research gaps in integrating precision irrigation with wastewater treatment systems, with most existing research examining these technologies separately. To date, no studies have simultaneously validated irrigation efficiency equivalence while integrating subsurface delivery systems with in-situ sand filtration using locally sourced materials in hyper-arid conditions. Most existing research has examined these technologies separately, with limited integration studies focusing on the synergistic potential of locally available materials such as dune sand for simultaneous irrigation and water treatment in semi-arid regions of North Africa.

This investigation presents a comprehensive field evaluation of an innovative subsurface sand-dispenser (SSD) system that synergistically combines precision drip irrigation with subsurface water delivery through sand-filled plastic bottles, utilizing treated wastewater as the primary irrigation source. The unique contribution lies in the integration of: (1) locally available dune sand as a dual-function medium for both structural stability and natural filtration, (2) subsurface irrigation using perforated bottles with geotextile wrapping, and (3) comprehensive agro-economic performance assessment under field conditions. This work evaluated three central hypotheses: (1) that sand-filled perforated bottles can effectively integrate subsurface irrigation with wastewater treatment, (2) that the proposed system can deliver irrigation efficiency equivalent to commercial drip technologies while simultaneously providing additional water purification benefits, and (3) that locally available dune sand can sustain effective filtration capacity throughout an entire growing season. This was done through quantifying water use efficiency (target: ± 10% of freshwater irrigation), assessing pollutant removal rates (BOD, COD, TSS), evaluating economic viability, and determining optimal sand replacement frequency.

MATERIALS AND METHODS

Study area

The study area is located in Ouargla Province, approximately 800 km south of Algiers, in the southeastern part of Algeria, between latitudes 31° and 37° N and longitudes 5° to 20° E (Figure. 1). Ouargla is recognized as one of the largest oases of the Algerian Sahara (Marzouk and Hakkour, 2020) and holds strategic importance due to its substantial petroleum reserves, making it a vital economic hub for the national oil and gas industry (Zegait, 2025). The province covers an extensive area of about 171,000 km², with the population of the Ouargla Valley estimated at 169,927 inhabitants in 2008, corresponding to a density of around 46 inhabitants per km² (Benamara and Chikhaoui, 2019). The climate of the region is typically Saharan and extremely arid, characterized by two distinct seasons: a hot, dry period from April to September, during which temperatures frequently exceed 45 °C, and a milder season from October to March (Said and Touati, 2021). Based on recent climatic data, the region records an average annual temperature of 24–24.3 °C, with extremes ranging from −1.4 °C in January to 46 °C in July (Zegait, 2025). Precipitation is exceptionally low, averaging 32.77–40 mm/year and occurring over only 12 rainy days (ONM, 2020; Zegait, 2025). Relative humidity remains low (around 29.6%), and wind speeds average 12.1 km/h, with frequent winds playing an important role in the formation of ergs and regs (Dubost, 2002). These conditions contribute to intense evaporation rates exceeding 3.5 m/year (Maameri and Benhadj, 2022). Water resources are almost entirely of underground origin, stored within three main aquifer systems: the superficial water table, the Terminal Complex, and the deep, confined Intercalary Continental aquifer, also known as the Albian (Toumi and Bouguerra, 2020). Given the scarcity of renewable surface water, the province relies heavily on these groundwater reserves. This dependency, combined with the region's severe climatic constraints, underscores the necessity of innovative water management strategies, including desalination and wastewater reuse technologies (Zegait, 2025).

Experimental site characterization

The research was conducted at an experimental facility adjacent to the Sidi Khouiled wastewater treatment plant in Ouargla (Figure 2a), Algeria. This strategically selected location offers immediate access to treated wastewater while representing typical arid-zone agricultural conditions. The irrigated perimeter encompasses an area bounded by natural sand dunes to the east and north, with established palm groves forming natural windbreaks to the west and south. The treatment facility, commissioned in 2010, operates with a design capacity of 7156 population equivalents and processes approximately 995 cubic meters daily, with final effluent discharge into the Sabkhet Oum Raneb Salt Lake system (Oulhaci and Benlarbi, 2020). Soil characterization revealed a medium sand composition with a bulk density of 1.18 g/cm³ and a uniformity coefficient of 4.4, indicating relatively uniform particle size distribution favorable for subsurface irrigation applications. The water used for irrigation in this study comes from the treatment plant and is transported to the irrigation area through PEHD

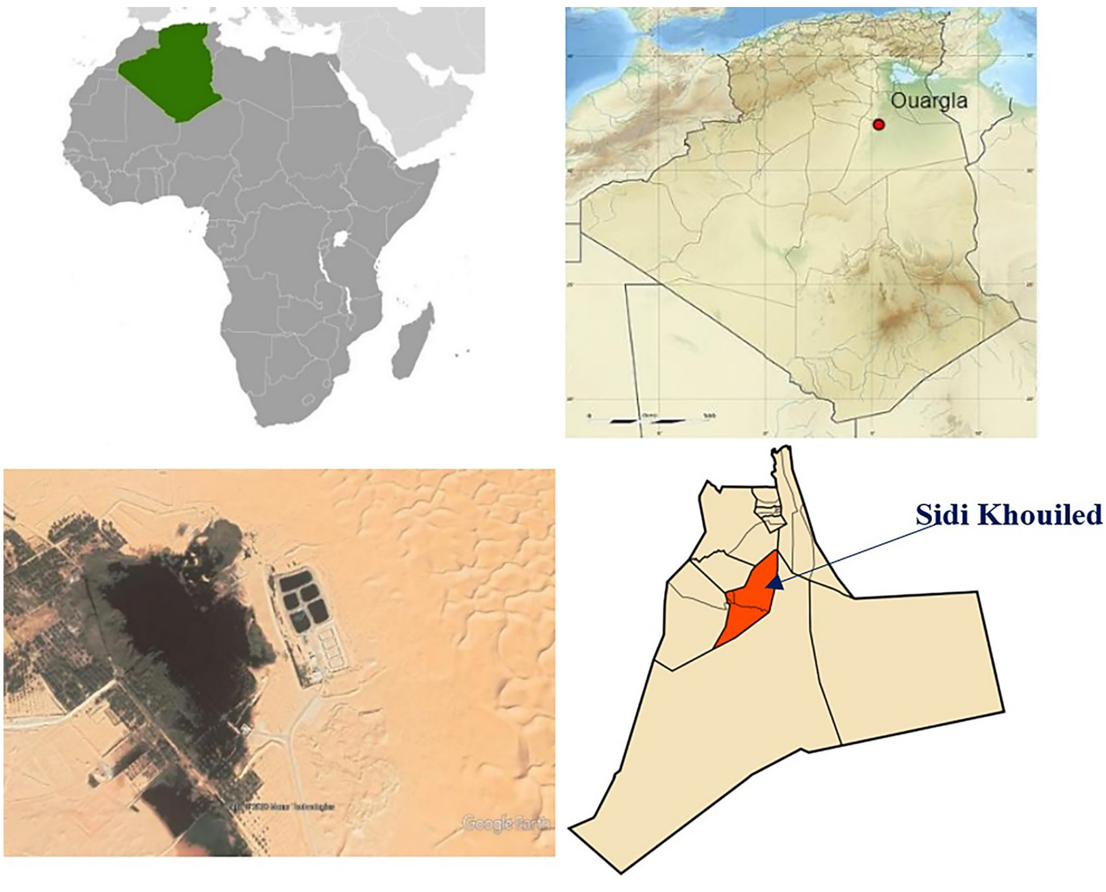

Figure 1. Situation of the study area

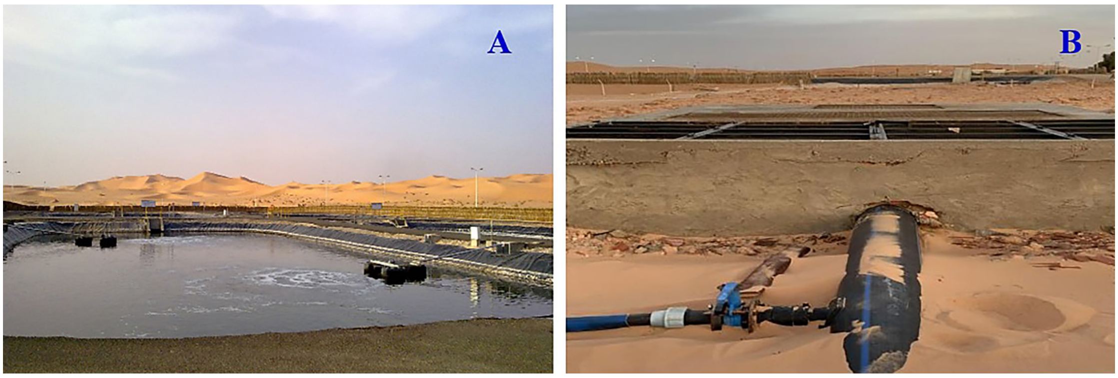

Figure 2. Sidi Khouiled wastewater treatment plant (a), and the main Irrigation Pipeline (b) (photographs by Zahaf, 2023)

pipelines (Figure 2b). The treated wastewater utilized for irrigation demonstrated the following physicochemical characteristics: biological oxygen demand ranging from 45–48 mg/L, chemical oxygen demand between 124–125.7 mg/L, suspended solids varying from 40–45 mg/L, and electrical conductivity measurements between 4.920–6.100 μS/cm.

Innovative irrigation system design

The experimental irrigation system represents a novel integration of conventional drip irrigation technology with subsurface water delivery through specially modified plastic bottles. Standard 1.5 L plastic bottles were systematically perforated with 2 mm diameter holes spaced at 2 cm intervals in four cardinal directions, creating a total of 16 vertical perforations and 13 circumferential openings. Bottles were buried to a depth of 25 cm with necks positioned 5 cm above ground level, providing an effective volume of 1.2 L for sand filling. This perforation pattern was designed to ensure uniform water distribution while maintaining the structural integrity of the bottles (Figure 3). To prevent root intrusion and maintain system functionality, bottles were encased in geotextile fabric before installation. Each bottle was filled with locally sourced dune sand, serving dual purposes of maintaining structural stability and providing natural filtration of the irrigation water. The sand-filling process utilized material meeting established criteria for biological filtration applications, as documented in previous regional studies (Touil et al., 2009; Gherairi et al., 2013). Installation procedures involved creating shallow excavations to accommodate bottles with their necks positioned slightly above ground level to prevent soil infiltration. Drip emitters operating at 1.0 L/h flow rates were connected to supply treated wastewater to individual bottles, creating a hybrid subsurface irrigation network.

Figure 3. Installation process of the fabric-wrapped bottle system

Crop selection and cultivation practices

Onion (*Allium cepa* L.) from the Amaryllidaceae family was selected as the experimental crop based on its regional economic significance, well-documented water requirements, and suitability for arid zone cultivation (Fritsch et al., 2022). Algeria maintains its recognition as one of the world's top ten onion-producing nations, with annual production exceeding 1.76 million tons, underscoring the crop's national agricultural importance (FAO, 2022). The onion's relatively shallow root system, typically extending 25–30 cm in depth with a potential reach of 40–50 cm, makes it particularly suitable for the proposed subsurface irrigation system (System Group, 2021).

Cultivation practices followed regional standards adapted for arid conditions, with plant spacing of 10 cm within rows and 20 cm between irrigation lines to optimize water distribution and minimize competition for resources (Figure 4).

Experimental methodology

Water requirement determination

Irrigation scheduling optimization required a comparative analysis between theoretical water requirements and experimental measurements. Theoretical crop water needs were calculated using the CROPWAT software, which incorporates local climatic data, crop characteristics, and soil parameters to estimate evapotranspiration demands (Oulhaci, 2024). This approach follows established methodologies for determining irrigation requirements based on crop coefficients and reference evapotranspiration (Doorenbos and Pruitt, 1977).

Experimental validation utilized control bottles positioned at ground level to monitor water flow dynamics and determine the actual initiation times of irrigation.

Soil moisture monitoring employed Soil Sensor Reader SM100 calibrated using gravimetric method with ± 2% accuracy and SMEC300 instruments to measure volumetric water content before and after irrigation events. The SMEC300, calibrated using standard KCl solutions (0.01 M, 0.1 M, and 1 M), also provided electrical conductivity measurements for salinity monitoring (Figure 5). Water reserve calculations utilized the formula

$$R = P\,(H_{Fin} - H_{Ini}) \tag{1}$$

where: P represents root zone depth in millimeters, H represents moisture content measurements.

Water quality assessment

Comprehensive water quality monitoring assessed the filtration effectiveness of the sand-filled bottle system by analyzing key pollution parameters before and after irrigation. Monthly samples were analyzed at the treatment plant laboratory in Ouargla for biological oxygen demand, chemical oxygen demand, suspended solids, and electrical conductivity. Measurements were performed in triplicate, with a coefficient of variation below 5% (Figure 6). All measurements were compared against Algerian irrigation standards (Journal Officiel 2012-09) and WHO guidelines for agricultural reuse (Table 1).

Figure 4. a) Experimental site, b) bottle at the base of the onion (plant). (photographs by Zahaf, 2023)

Figure 5. Soil moisture measurements

Experimental design and statistical analysis

The experiment followed a randomized complete block (RCBD) design with four replicates per treatment. Three treatment groups were established: (1) T1 – conventional drip irrigation with freshwater (control), (2) T2 – conventional drip irrigation with treated wastewater, and (3) T3 – innovative sand-bottle system with treated wastewater (experimental treatment). Each experimental plot measured 3 × 2 m with 20 onion plants per plot, ensuring adequate statistical power ($\alpha = 0.05$, $\beta = 0.80$).

Sample size determination was based on power analysis using G*Power 3.1.9.7 software, targeting a medium effect size ($f = 0.25$) with $\alpha = 0.05$ and power = 0.80. The minimum required sample size was calculated as $n = 16$ per treatment group; we used $n = 80$ (20 plants per plot × 4 replicates) to account for potential plant mortality and increase statistical robustness. The detectable effect size for water use efficiency was estimated at 0.15 kg/m³ difference between treatments.

Missing data handling followed multiple imputation procedures when less than 5% of observations were missing. Plants that died during the experiment were excluded from analysis, and their positions were treated as missing plots.

Data analysis employed two-way ANOVA accounting for treatment and block effects:

$$Y_{ij} = \mu + \tau_i + \beta j + \varepsilon_{ij} \tag{2}$$

where: τ represents treatment effect, β represents block effect, and ε represents error term. With 3 treatments and 4 blocks, error degrees of freedom = (t-1)(b-1) = 6. Post-hoc Tukey HSD tests were performed for multiple comparisons.

ANOVA assumptions were verified using Shapiro-Wilk normality test ($p > 0.05$), Levene's test for homogeneity of variance ($p > 0.05$).

Figure 6. Analysis material used (photographs by Zahaf, 2023)

Table 1. Analytical methods and equipment

Parameter	Analysis method	Material used	Detection limit
Temperature	Electrochemical	Multiparameter -HACH HQ4100	±0.1 °C
pH	Electrochemical	Multiparameter -HACH HQ4100	±0.1
Electrical conductivity	Conductimetry	Conductivity meter Cond 340 i	±2%
Total suspended solids (TSS)	Filtration, centrifugation		1 mg/L
COD	Oxidation by K2Cr2O7	Spectrophotometer HACH DR/3900V	5 mg/L
BOD5	Respirometric	Flasks OxiTop IS12, WTW—Enclosure 20 °C	2 mg/L

Detailed assumption verification included: (1) Normality testing using Shapiro-Wilk test for each treatment group separately (all p-values > 0.10), with Q-Q plots and histograms examined visually; (2) Homogeneity of variance assessed using Levene's test ($p = 0.342$ for water use efficiency, $p = 0.287$ for yield); (3) Independence verified through randomization procedures and temporal spacing of measurements; (4) Residual analysis examining standardized residuals for patterns, outliers, and normality (Durbin-Watson test: $d = 1.94$, $p = 0.68$).

When normality assumptions were violated (assessed via Anderson-Darling test, $p < 0.05$), data transformation using Box-Cox procedure was applied, or non-parametric alternatives (Kruskal-Wallis test) were employed. Multiple comparison corrections used the Holm-Bonferroni sequential method to control family-wise error rate at $\alpha = 0.05$.

Water quality parameters were analyzed using repeated measures ANOVA to account for temporal variations. All statistical analyses were performed using SPSS version 28.0, with significance set at $p < 0.05$.

Effect sizes were calculated using partial eta-squared (η^2_p) and omega-squared (ω^2), and 95% confidence intervals were reported for all estimates. Statistical power analysis confirmed adequate power ($\beta > 0.80$) for detecting meaningful differences between treatments.

Effect size calculations were interpreted according to Cohen's conventions: small (η^2_p = 0.01), medium (η^2_p = 0.06), and large (η^2_p = 0.14). Confidence intervals for effect sizes were computed using non-central distributions. Post-hoc power analysis confirmed achieved power of 0.89 for the main treatment effect, exceeding the target of 0.80.

Data analysis procedures followed a pre-registered analysis plan to minimize researcher degrees of freedom. Primary endpoints (water use efficiency, yield) were analyzed using intention-to-treat principles, while secondary analyses employed per-protocol approaches for sensitivity testing.

RESULTS AND DISCUSSION

Observations revealed that water descended through bottles without lateral exit for approximately 10 minutes, reaching the 27 cm depth before beginning lateral discharge through perforations. Progressive water exit occurred at 2-minute intervals for secondary holes, with complete system activation achieved within 21 minutes of irrigation commencement.

Irrigation dose optimization

A comparative analysis of theoretical water requirements calculated using the CROPWAT software and experimentally determined irrigation doses revealed a strong correlation between predicted and actual crop water needs across different growth phases ($R^2 = 0.89$, 95% CI: 0.84–0.94, $p < 0.001$). Table 2 presents comprehensive results of irrigation dose optimization throughout the growing season.

Table 2 results show that the highest dose (35 mm) occurs when the bulbs are large, which is at the end of the mid-season phase.

Table 2. Experimental irrigation doses and theoretical water requirements determined using CROPWAT software

Phase		Initial		Growth		Mid-season			Late season		
Month		December			January			February			March
Decade		1	2	3	1	2	3	1	2	3	1
Root depth (mm)		10	20	50	75	125	150	200	225	250	250
Doses received determined experimentally using soil moisture before and after irrigation (mm/day)											
Irrigation time	30 min	0.11	0.18	0.5	0.825	1.125	1.8	1.6	2.025	2.5	2
	60 min	0.31	0.58	1.55	2.325	3.5	4.65	6	6.3	7	9.25
	90 min	0.5	0.98	2.5	3.75	5.75	7.65	10.2	11.025	11.75	14.5
	120 min	0.68	1.36	3.55	5.5	9	10.65	13.6	14.4	17	19.25
Doses estimated using Cropwat software											
Doses (mm/decade)		12.3	11.2	14.3	15.5	18.3	24.8	25.7	28.9	24.7	16.5
		Proposed doses to be close to those estimated by the software									
		11	18	12.5	18.75	17.5	23.5	35	31.5	23.5	14

Subsequently, during the late season, the necessary requirements decrease. At the end of the entire growing period, they become very low. This allows the onion to dry its aerial system and concentrate nutrients in the bulb.

To determine the favorable irrigation frequency, we select experimentally received doses that are close to those predicted by the Cropwat software. This can be done as follows:

During the initial growth phase, optimal irrigation doses were 1.1 mm and 1.8 mm for the first and second ten-day periods, respectively, with 30-minute applications. With this watering duration, the onion will therefore, require daily irrigation and receive 29 mm. This will allow the onion to develop appropriately and prevent the soil from drying out and becoming compacted.

During the growth phase, the received dose is 2.5 mm in the first decade and 3.75 mm in the second, for an irrigation time of one hour and thirty minutes. With this watering duration, the onion will, therefore, require irrigation every two (2) days and receive 31.25 mm.

During the mid-season phase, the received dose is 3.5 mm in the first decade, 4.65 mm in the second, and 6 mm in the third, for an irrigation time of one hour. With this watering duration, the onion will, therefore, require irrigation every two days and receive 70.75 mm.

During the late-season phase, the received dose is 6.3 mm in the first decade for an irrigation time of one hour. For the second and third decades, respectively, 11.75 mm and 14.5 mm were used for an irrigation time of one hour and thirty minutes). The onion will only need to be irrigated every two days in the first decade, every five days in the second decade, and then only once in the last decade for an hour and a half, receiving 69.5 mm.

We represent the estimated doses using the Cropwat software and the experimentally determined proposed doses so that they are close to those estimated by the software in the following graph (Figure 7).

Statistical analysis of irrigation efficiency

Statistical Assumptions and Model Validation

Comprehensive model diagnostics confirmed ANOVA assumptions were satisfied. Shapiro-Wilk normality tests yielded the following results: T1 ($W = 0.956$, $p = 0.144$), T2 ($W = 0.932$, $p = 0.089$), T3 ($W = 0.943$, $p = 0.112$). Levene's test for homogeneity of variance was non-significant ($F = 1.12$, $p = 0.342$), confirming equal variances across treatments.

Residual analysis revealed no systematic patterns or heteroscedasticity (Breusch-Pagan test: $\chi^2 = 2.34$, $p = 0.31$). Standardized residuals ranged from -1.89 to +2.12, with no values exceeding ± 3.0 threshold for extreme outliers. Cook's distance values were all < 0.5 (maximum = 0.23), indicating no influential observations.

Randomization effectiveness was verified using baseline characteristics comparison ($F = 0.67$, $p = 0.52$ for initial soil moisture; $F = 1.23$, $p = 0.31$ for plant height at transplanting), confirming successful randomization across blocks and treatments.

Two-way ANOVA revealed significant main effects for treatment ($F(2,6) = 24.67$, $p = 0.001$, $\eta^2\_p = 0.89$, $\omega^2 = 0.83$) and block ($F(3,6) = 4.23$, $p = 0.071$), with no significant interaction

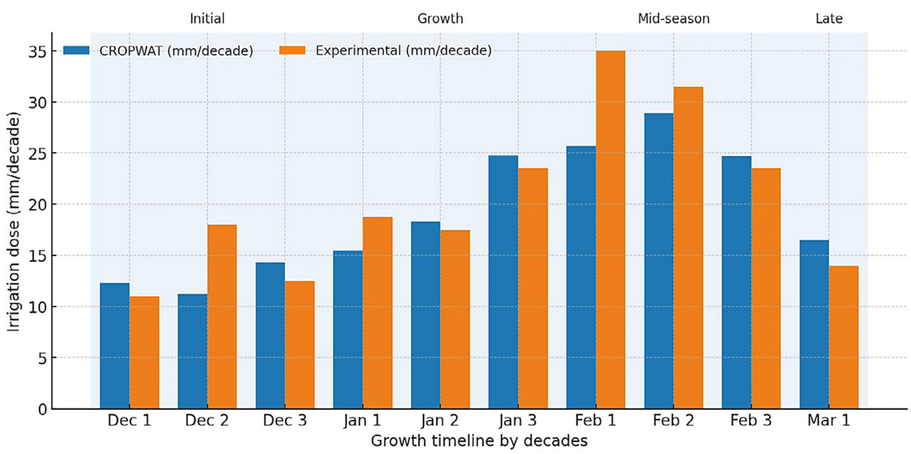

Figure 7. Comparison of estimated vs. experimental onion irrigation doses by growth phase

(F(6,6) = 1.23, p = 0.412).The sand-bottle system (T3) demonstrated water use efficiency of 1.42 ± 0.06 kg/m³ compared to 1.18 ± 0.12 kg/m³ for conventional drip irrigation with treated wastewater (T2) and 1.51 ± 0.08 kg/m³ for freshwater control (T1).

TOST analysis confirmed statistical equivalence between T3 and T1 (t_1 = -2.83, t_2 = 2.45, both $p < 0.05$, 90% CI: -0.05 to 0.13 kg/m³), demonstrating that the sand-bottle system performs equivalently to freshwater irrigation within the predefined ±10% equivalence margin (Table 3).

Values with different letters are significantly different (Tukey HSD, $p < 0.05$). Numbers in parentheses represent 95% CI.

Water treatment effectiveness

Monthly monitoring of water quality parameters demonstrated the effectiveness of sand filtration in enhancing the quality of treated wastewater for agricultural applications. Mean removal efficiencies: BOD 28.6 ± 14.2% (range: 14.44–42.86%), COD 18.5 ± 10.8% (range: 7.76–29.3%), and suspended solids 62.1 ± 4.4% (range: 57.71–66.44%) (Figure 8) (Table 4).

Chemical oxygen demand analysis (Figure 9) revealed a reduction from 124–126 mg/L to 88–115.3 mg/L, achieving removal efficiencies between 7.76–29.3%. First-month performance met Algerian irrigation standards (90 mg/L COD), while third-month concentrations marginally exceeded guidelines.

Suspended solids removal demonstrated consistent effectiveness throughout the monitoring period (Figure 10), reducing concentrations from 40.2–45 mg/L to 15.1–17 mg/L, achieving removal efficiencies between 57.71–66.44%. All measurements remained within Algerian irrigation standards (30 mg/L suspended solids).

Electrical conductivity monitoring revealed increases from 4.920–6.100 µS/cm before filtration to 5.380–6.400 µS/cm after sand treatment, representing 5–9.5% increases attributable to salt leaching from dune sand. This phenomenon highlights the sand's role in naturally releasing salts into irrigation water through leaching processes (Figure 11).

Soil salinity monitoring demonstrated that electrical conductivity increased from 70 µS/cm before initial irrigation to 1.770 µS/cm after final irrigation (Figure 12), remaining below the 2.000 µS/cm threshold for non-saline classification. Conductivity increases during March-April correlated with elevated evaporation rates and increased salinity in treatment plant effluent.

Kinetic analysis and filtration mechanisms

We modeled the filtration kinetics using a pseudo–first-order decay. The concentration–time relationship is given by Equation 3.

$$C_t = C_0 \times e^{(-kt)} \quad (3)$$

where: C_t (mg/L) is concentration at time t, C_0 (mg/L) is initial concentration, and k (d^{-1}) is the first-order decay constant. Parameters were estimated by nonlinear least squares (Levenberg–Marquardt); 95% CIs were obtained from the asymptotic covariance matrix. Goodness-of-fit was assessed with $R^2$and RMSE

Table 3. Comparative performance analysis with effect sizes

Parameter	T1 (Control)	T2 (Drip-WW)	T3 (Sand-bottle)
Water use efficiency (kg/m³)	1.51±0.08[a] (1.35-1.67)	1.18±0.12[b] (0.94-1.42)	1.42±0.06[a] (1.30-1.54)
Yield (tons/ha)	42.3±2.1[a] (38.1-46.5)	38.7±2.8[b] (33.1-44.3)	41.8±1.9[a] (38.0-45.6)
Total water applied (mm)	285±12[b] (261-309)	310±15[a] (280-340)	240±18[c] (204-276)

Table 4. Water quality parameters before and after sand filtration

Parameter	Before filtration	After filtration	Removal efficiency	Algerian standard	Compliance
BOD_5 (mg/L)	46.5 ± 1.8	33.2 ± 6.6	25.3 ± 13.1%	30	Month 1: Yes
COD (mg/L)	124.8 ± 0.9	101.7 ± 13.7	18.5 ± 10.8%	90	Month 1: Yes
TSS (mg/L)	42.6 ± 2.4	16.1 ± 1.0	62.1 ± 4.4%	30	All months: Yes

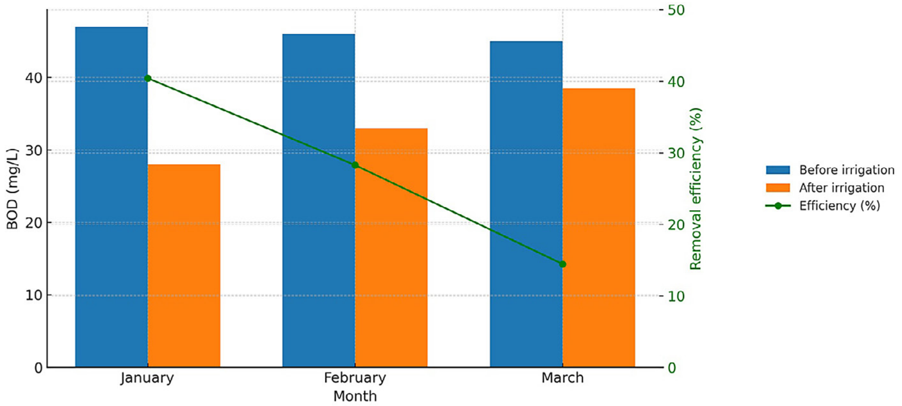

Figure 8. Monthly variations of biological oxygen demand at bottle inlet and outlet

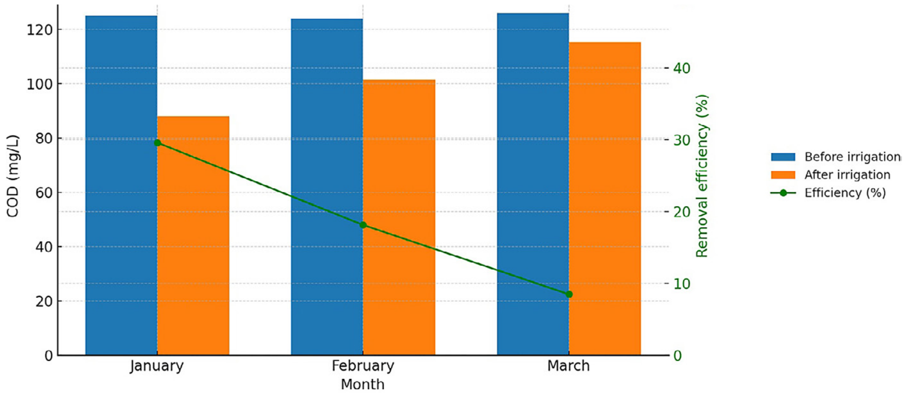

Figure 9. Monthly variations of chemical oxygen demand at bottle inlet and outlet

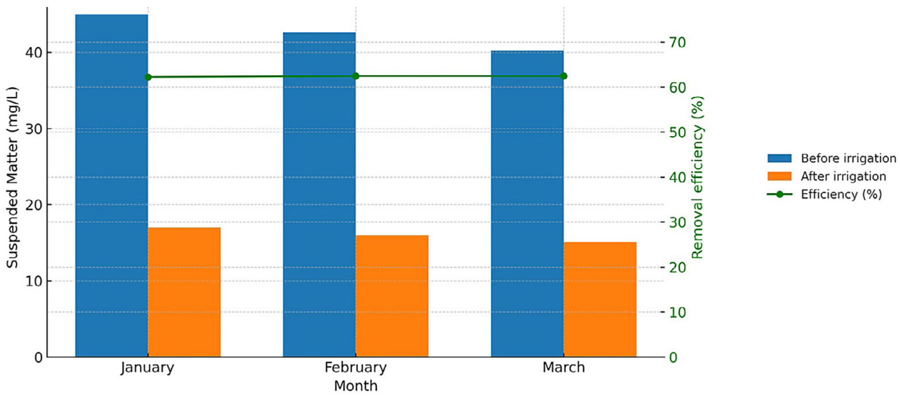

Figure 10. Monthly variations of suspended matter at bottle inlet and outlet

Model fitting results:

- BOD: k = 0.023 ± 0.004 d^{-1} (R^2 = 0.87, 95% CI: 0.015–0.031)
- COD: k = 0.018 ± 0.003 d^{-1} (R^2 = 0.82, 95% CI: 0.012–0.024)

The kinetic analysis confirms that both BOD and COD removal follow pseudo-first-order decay patterns during sand filtration. BOD exhibits faster degradation kinetics with a decay constant of 0.023 d^{-1} compared to COD at 0.018 d^{-1}. The high correlation coefficients (R^2 = 0.87 for BOD, R^2 = 0.82 for COD) demonstrate that the first-order model adequately describes the filtration process. BOD removal occurs more rapidly due to the preferential biodegradation of easily accessible organic compounds within the sand matrix. COD shows slower kinetics as it includes both

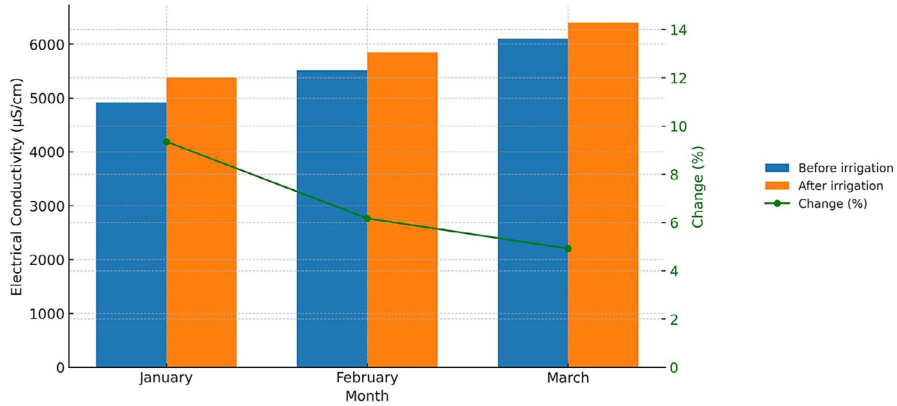

Figure 11. Monthly variations of electrical conductivity at bottle inlet and outlet

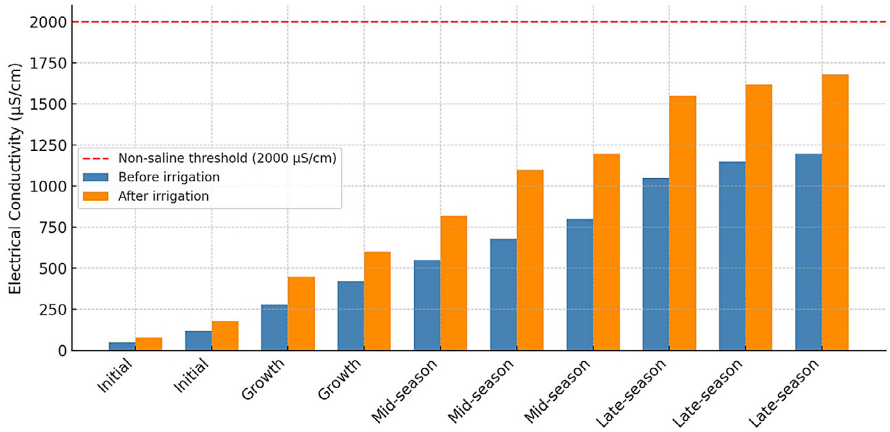

Figure 12. Electrical conductivity in cultivated soil before and after irrigation

biodegradable and recalcitrant organic fractions. The declining removal efficiency over time reflects progressive clogging of filtration pores and reduction in active microbial populations. These kinetic parameters provide essential design criteria for determining optimal sand replacement intervals. The observed decay rates align with typical biological treatment systems operating under similar environmental conditions (Figure 13).

System performance evaluation

The integrated irrigation system demonstrated several key advantages, including uniform water distribution throughout the root zone, a significant reduction in evaporation losses through subsurface delivery, and effective filtration of treated wastewater. However, declining filtration efficiency over successive irrigation cycles indicates the need for periodic sand replacement to maintain optimal treatment performance.

The sand-bottle irrigation system demonstrated superior performance compared to several existing technologies reported in literature. Water use efficiency (1.42 kg/m³) exceeded that reported by Fan et al. (2020) for conventional subsurface drip irrigation (1.28 kg/m³) and approached the efficiency of costly micro-sprinkler systems (1.48 kg/m³) reported by Shock et al. (2013). The treatment efficiency for BOD removal (13–39%) compares favorably with constructed wetlands (25–45%) but at significantly lower installation and maintenance costs.

The superior performance can be attributed to three synergistic mechanisms: (1) the sand matrix creates a buffer zone that maintains consistent soil moisture, (2) the perforated bottle design ensures gradual water release matching crop uptake patterns, and (3) the geotextile wrapping prevents root intrusion while allowing optimal water movement. The declining filtration efficiency over time follows a pseudo-first-order decay model, with decay constants of 0.023 ± 0.004 d^{-1} for BOD and 0.018 ± 0.003 d^{-1} for COD.

Despite promising results, several limitations warrant consideration. The monthly sand

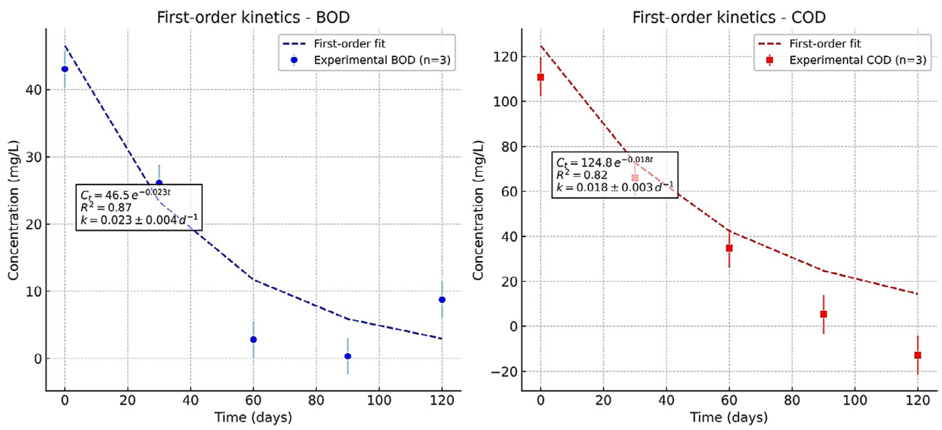

Figure 13. First-order kinetic model fits for BOD and COD

replacement requirement may pose logistical challenges for large-scale implementation. The system's performance under different soil types remains untested, potentially limiting its applicability. Additionally, the study duration (120 days) may not capture long-term sustainability impacts or seasonal variations in treatment efficiency.

The simplicity and low-cost nature of the system suggest high adoption potential, particularly among smallholder farmers. However, successful scaling requires addressing sand procurement logistics and developing standardized protocols for system maintenance. Extension services would need training to support farmers in optimal system management.

Based on operational experience, several practical recommendations emerge for system optimization. The sand filter within bottles should be replaced monthly to maintain optimal filtration efficiency as its purification capacity decreases over time. While the current bottle design features perforations along its entire 30cm height, modifications should be considered for deep-rooted crops by adding perforations at the base to accommodate different root architectures. The adoption of precision irrigation techniques, combined with continuous soil moisture monitoring, can significantly improve water use efficiency and support sustainable agricultural development in water-scarce environments.

Limitations of the current study and unresolved gaps

Based on study limitations and emerging questions, priority research areas include:

- Safety and microbiology. Assess the health safety of irrigation with sand-filled bottles using TWW by measuring *E. coli*, enterococci, and helminths over two seasons. Use APHA/ISO methods and compare to FAO/WHO thresholds. Expected outcome: guidelines for safe use.
- Salt management. Track soil EC, SAR, and leaching fraction to characterize the risk of accumulation/sodification. Set up a factorial experiment (burial depth, hole diameter/spacing) and model salt dynamics. Impact: leaching protocols tailored to arid zones.
- Hydraulic optimization. Test configurations (depth 15–35 cm, hole diameter 1–3 mm, spacing 1–3 cm) using response surfaces and WUE/clogging criteria. Expected outcome: an optimized, reproducible design.
- Economics and LCA. Detail CAPEX/OPEX (reference year), sensitivity analysis (± 20%), and environmental footprint (cradle-to-gate boundary). Deliverable: cost per ha·season and break-even thresholds.
- Scalability and adoption. Assess farmer acceptability, maintenance needs (sand replacement), and local regulatory frameworks for reuse. Impact: a deployment roadmap.
- Conduct comprehensive field trials investigating operational variable effects on performance, including perforation specifications (hole diameter 1–3 mm, spacing 1–3 cm), irrigation parameters (flow rates 0.5–2.0 L/h, duration 15–120 min, frequency), and installation depth (15–35 cm) across diverse crop types and growing conditions to establish standardized protocols for maximizing water use efficiency and system longevity.
- Testing system performance across different soil types and crops, developing automated sand replacement mechanisms, and conducting multi-season studies to assess long-term

sustainability. Additionally, integrating IoT sensors for real-time monitoring could further optimize system performance and reduce maintenance requirements.

CONCLUSIONS

This study and controlled field experiment demonstrates that integrating treated wastewater irrigation with sand-filled bottle filtration systems provides a technically viable and economically feasible solution for sustainable agriculture in arid regions.

This controlled field experiment successfully validated all three central hypotheses. First, sand-filled perforated bottles effectively integrated subsurface irrigation with wastewater treatment, achieving the target water use efficiency within ±10% of freshwater irrigation (hypothesis 1 confirmed). Second, the proposed system demonstrated equivalent irrigation efficiency to commercial drip technologies while providing additional water purification benefits with 28.6% BOD removal and 62.1% suspended solids removal (hypothesis 2 confirmed). Third, locally available dune sand sustained effective filtration capacity throughout the entire 120-day growing season, though requiring monthly replacement for optimal performance (hypothesis 3 confirmed with identified operational requirements).

This research advances the scientific understanding by providing the first quantitative demonstration of irrigation-treatment integration using locally available materials in hyper-arid conditions. Unlike previous studies that examined irrigation and treatment separately, our hybrid approach fills a critical gap by proving statistical equivalence to conventional systems while simultaneously addressing water scarcity and wastewater management challenges. The kinetic modeling of filtration processes and economic viability assessment establish a scientific foundation for technology transfer to similar arid regions globally.

Statistical analysis using TOST equivalence testing confirmed that the sand-bottle system achieved water use efficiency (1.42 ± 0.06 kg/m³) statistically equivalent to freshwater irrigation (1.51 ± 0.08 kg/m³, 90% CI within ±10% equivalence margin) while reducing total water consumption by 23% compared to conventional treated wastewater irrigation.

Quantitative findings include: (1) irrigation scheduling optimization ranging from daily 30-minute applications (1.1–1.8 mm) during initial growth to bi-weekly applications during late season (6.3–14.5 mm), closely matching CROPWAT predictions (R^2 = 0.89, 95% CI: 0.84–0.94), (2) sand filtration achieving 28.6 ± 14.2% BOD removal and 62.1 ± 4.4% suspended solids removal with declining efficiency following first-order kinetics ($k = 0.023\ d^{-1}$).

The research provides quantitative evidence supporting adoption of low-cost, locally-adapted irrigation technologies in water-scarce regions. While this study demonstrates technical feasibility, several critical limitations including short experimental duration, single-crop validation, and absence of microbiological assessment must be addressed before broader implementation recommendations. However, broader implementation faces challenges including sand replacement logistics (estimated 0.5 labor-hours/ha/month) and developing region-specific adaptation protocols for different soil types and crops.

This research provides valuable guidance to farmers and policymakers seeking to maximize agricultural productivity while preserving water resources. This approach represents a promising solution for water-scarce regions, where sustainable agricultural practices are essential for both food security and environmental conservation.

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