Research Square

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Root-zone injection (Waterlow®) versus surface drip irrigation for date palm in a hyper-arid Tunisian oasis: a preliminary wetting-front comparison under extreme summer conditions

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Abstract

In hyper-arid oases, limiting surface wetting may reduce non-productive soil evaporation from localized irrigation. This exploratory field study compared a buried root-zone injector (Waterlow®) with a surface drip emitter on one 10-year-old date palm (*Phoenix dactylifera* L.) in Douz, southern Tunisia. Tests were conducted on 29 June and 5 August 2025 (41°C and 51% relative humidity; 49°C and 21%, respectively), after eight days without irrigation. Both systems used nominal 4 L h^{-1} emitters located 60 cm from the trunk. Applied water, irrigation duration, applied fertilizer-solution volume and geometrically estimated wetted soil volume were recorded until a moisture sensor installed at 60 cm depth responded. Waterlow® required 2.5 L to reach this endpoint, compared with 29 L (June) and 36 L (August) for surface drip, i.e. 91–93% less applied water. Durations were 40–42 min and 420–540 min, respectively, while mean discharges were similar (3.6–4.1 L h^{-1}). Applied fertilizer-solution volumes were 1.5 L and 9–11 L. Estimated wetted soil volumes were 78,500 cm^3 for Waterlow® and 113,040–116,840 cm^3 for surface drip. Because water was released below the surface, the vertical distance to the sensor was shorter with Waterlow®, which partly explains the difference. These single-palm, single-event observations describe wetting behaviour only; they do not quantify seasonal water savings, nutrient delivery, energy use or yield effects. Replicated trials with calibrated sensors and seasonal water and salt balances are needed.

1 Introduction

Date palm (*Phoenix dactylifera* L.) is the main crop of the Saharan oases of southern Tunisia and the basis of their economy. Its irrigation depends almost entirely on deep groundwater from the Complexe Terminal and Continental Intercalaire aquifers. The expansion of irrigated areas over recent decades has lowered groundwater levels and increased the salinity of irrigation water in the Nefzaoua region, which includes Douz (Dhaouadi et al. 2021; Zammouri et al. 2007). Excess irrigation combined with poor drainage also causes waterlogging and soil salinization in oasis plots (Dhaouadi et al. 2022a; Marlet et al. 2009). Climate projections indicate that warming and the rising salinity of irrigation water will further increase the irrigation demand of date palms in Tunisian oases (Haj-Amor et al. 2020).

Date palm has a high water requirement in hyper-arid climates, and its growth and yield decline as soil salinity increases (Al-Muaini et al. 2019; Tripler et al. 2011). In Douz, the average annual net irrigation requirement of date palm has been estimated at about 2400 mm (Haj-Amor et al. 2018), while CROPWAT-based estimates for other Tunisian oases are 1045–1267 mm (Tiba et al. 2025). In practice, farmers often apply much more water than the crop needs, and the water productivity of date palm in Tunisian oases remains low (Dhaouadi et al. 2022b). Improving the way water is applied to each palm is therefore a key lever for saving groundwater.

Several irrigation systems are currently used under date palm. They can be grouped into (i) traditional surface irrigation by basin or submersion, (ii) localized surface systems such as drip, bubbler and micro-jet irrigation, and (iii) subsurface systems, mainly subsurface drip irrigation (SDI) (Liebenberg and Zaid

2002). Surface irrigation, in which the basin around the palm or the whole plot is flooded during each water turn, is still the dominant method in Tunisian oases. In Douz, its performance depends strongly on soil texture, plot size and farmers' practices, especially irrigation duration (Haj-Amor et al. 2018). The application efficiency of surface irrigation in a Tunisian oasis has been estimated at only 37%, and raising it to 70% could save up to 1980 mm of water per year (Haj-Amor and Acharjee 2021).

Localized irrigation has been promoted to reduce these losses. Drip irrigation improved the uniformity and efficiency of water application in date palm orchards of the Degueche oasis (Dhaouadi et al. 2017), and automated drip systems improved water productivity, yield and fruit quality of date palm in Saudi Arabia (Alnaim et al. 2022). Bubbler irrigation, which delivers water to a small basin around each palm, is well suited to the high water demand of mature trees. In a southern Tunisian oasis, date palm water productivity under bubbler irrigation was about three times that under traditional submersion irrigation (Ben Maachia et al. 2026). However, bubblers distribute water less uniformly than drippers (Abd El-Aziz and Fayed 2025). With all surface localized systems, the wetted soil surface remains exposed to very high evaporative demand, so part of the applied water is lost by soil evaporation (Allen et al. 1998; Kool et al. 2014), and frequent shallow wetting encourages root development near the surface (Alnaim et al. 2022; Bourziza et al. 2017).

Subsurface drip irrigation places water directly in the root zone and keeps the soil surface dry. It has been widely studied in row crops (Ayars et al. 1999; Camp 1998; Lamm et al. 2012) and, more recently, in date palm. In Oman, palms irrigated by SDI at 60% of crop evapotranspiration produced the same yield as palms irrigated by bubblers at 100%, corresponding to about 40% water saving (Al Wahaibi et al. 2018). In Saudi Arabia, SDI increased water use efficiency by 27% compared with surface drip (1.32 vs 0.96 kg m^{-3}) without affecting yield (Dewidar and Ben-Salah 2016), and economic analyses showed that, despite higher installation costs, SDI is profitable in the long term (Dhehibi et al. 2022). Positive results were also reported for young date palms in Morocco (Bourziza et al. 2017). Nevertheless, SDI requires careful design and maintenance: emitter clogging, root intrusion, salt accumulation above the laterals and the cost of installing buried lines around large trees remain important constraints (Camp 1998; Hanson et al. 2008; Lamm et al. 2012). In addition, the shape of the wetted zone around buried emitters depends strongly on soil hydraulic properties (Cote et al. 2003).

A simpler alternative to buried laterals is to deliver water at depth through individual point sources placed near each plant. Traditional methods such as buried clay pots and porous clay pipes have long been used in dry regions to irrigate trees with little surface wetting (Bainbridge 2001; Siyal and Skaggs 2009). More recently, direct root-zone irrigation, which releases water through vertical tubes at 30–90 cm depth, maintained grapevine yield with less water than surface drip and modified root distribution in a loamy sand soil (Ma et al. 2019, 2020). Waterlow® is a commercial device based on this principle: a vertical injector, fed by a standard surface dripper, releases water into the root zone through a buried, fabric-wrapped section (Waterlow 2026). Because it can be connected to existing drip lines, it could offer oasis farmers a low-cost way to move from surface to subsurface delivery. However, to our knowledge,

no independent field evaluation of this type of device has been reported for date palm in hyper-arid oasis soils.

This preliminary study compared Waterlow® with surface drip irrigation on a date palm in Douz during two extreme summer events. The objectives were to quantify, for each system, (i) the volume of water and (ii) the irrigation time required to obtain a sensor response at 60 cm depth, (iii) the applied volume of fertilizer solution to the same endpoint, and (iv) the geometrically estimated wetted soil volume. The results are interpreted as event-scale wetting behaviour, not as seasonal water savings.

2 Materials and methods

2.1 Study site

The study was conducted in a date palm plantation in Douz (Kebili Governorate, southern Tunisia), under a hyper-arid climate. One 10-year-old date palm (cultivar: Deglet Nour) planted at 7 × 7 m spacing was used. The soil was a loamy sand (USDA classification; 82% sand, 4% silt and 14% clay).

2.2 Waterlow® device

The Waterlow® injector (Fig. 1) consists of a 50 cm long, 16 mm diameter low-density polyethylene (LDPE) tube perforated near its lower end. The perforated section is surrounded by an inert mineral layer contained in a non-woven fabric pouch, which limits soil and root intrusion. The upper end is closed by a high-density polyethylene (HDPE) cap with a 5 mm air inlet, and a 5 mm lateral fitting located about 30 cm from the lower end receives the water.

In the field, a nominal 4 L h^{-1} Key Klip LMB emitter on the surface irrigation pipe feeds a 25 cm flexible 4/6 mm PVC microtube connected to the lateral fitting of the injector (Fig. 2). The microtube descends from the emitter to the inlet, so that water flows by gravity into the tube and is released through the buried perforated section. Redistribution in the soil is then governed by matric potential gradients, hydraulic conductivity and gravity.

2.3 Experimental set-up

One Waterlow® injector and one surface dripper were installed around the same palm, each about 60 cm from the trunk on opposite sides of the palm?. The injector was installed so that its outlet was at about 30 cm depth please confirm the depth of the perforated section; the surface dripper was placed on the soil surface. Each treatment was supplied with a nominal 4 L h^{-1} emitter. This was therefore an unreplicated, single-palm comparison on two dates, not a randomized trial.

Each system was supplied from its own 20 L container, graduated every 0.5 L and placed about 1 m above the ground. Applied volume was read on the container and elapsed time was recorded. Because

the hydraulic head decreased as the container emptied, the mean effective discharge of each event was calculated as applied volume divided by duration.

A five-pin RS485 multifunction soil sensor model, manufacturer was installed at 60 cm depth near each treatment and read on a smartphone. The sensor displayed moisture, temperature and NPK-related indicators. The test endpoint was defined as the first clear increase in the moisture reading at 60 cm please state the threshold used, e.g. increase of x units or reading > y%. Before each test, irrigation had been withheld for eight days and both sensors showed initial readings of 45–50% on the instrument scale. Low-cost dielectric sensors need soil-specific calibration, because their response depends on soil texture, bulk density, temperature and salinity (Adla et al. 2020; Placidi et al. 2020). As the sensor was not calibrated for this soil, the endpoint is a sensor-indicated arrival of the wetting front, not a measured soil water content or saturation.

After each test, the lateral extent and upper limit of the wetted zone were delineated with a 30 cm single-probe moisture meter (Hathdia) please state probe positions and the criterion used to define the wetted boundary. Observations suggested an approximately cylindrical wetted zone. Wetted soil volume is a common design criterion for localized irrigation (Zur 1996); it was therefore estimated as $V_w = \pi r^2 h$, where r is the measured wetted radius and h the vertical extent of the zone between 20 and 60 cm depth. The 0–20 cm layer was excluded because the Waterlow® wetted zone did not extend above about 20 cm. This approximation describes the soil volume reached by the wetting front, not the quantity or uniformity of stored water.

Fertilizer tests followed the same procedure with an organic liquid fertilizer diluted 1:15 v/v? product name and composition, applied from graduated containers until the sensor response at 60 cm. Please specify whether fertilizer tests were made on separate days after the same 8-day drying period, or after the water tests. Because a moisture sensor cannot detect dissolved nutrients, these values are reported as applied solution volumes to the moisture endpoint, not as nutrient delivery.

Air temperature and relative humidity (RH) were measured in the shade at about 14:00: 41°C and 51% on 29 June 2025, and 49°C and 21% on 5 August 2025. Relative reductions were computed as 100 × (drip value − Waterlow® value)/drip value. No statistical test was applied because treatments were not replicated.

3 Results

3.1 Applied water, irrigation duration and discharge

Waterlow® required 2.5 L of water to trigger the sensor response at 60 cm on both dates, compared with 29 L in June and 36 L in August for surface drip (Table 1). This corresponds to 91.4% and 93.1% less applied water. The time to reach the endpoint was 40 and 42 min with Waterlow® versus 420 and 540 min with surface drip (90.5% and 92.2% shorter). Mean effective discharges were similar for both

systems (3.6–3.8 L h^{-1} for Waterlow® and 4.0–4.1 L h^{-1} for drip) and close to the nominal 4 L h^{-1}. The difference in applied volume therefore resulted from the time needed to reach the endpoint, not from different emitter flow rates. For surface drip, 7 L (24%) more water and 120 min more were needed in August than in June.

Table 1
Applied water, irrigation duration, mean discharge and applied fertilizer-solution volume required to obtain a sensor response at 60 cm depth

Date (conditions)	System	Water applied (L)	Duration (min)	Mean discharge (L h^{-1})	Fertilizer solution (L)
29 June (41°C; RH 51%)	Waterlow®	2.5	40	3.75	1.5
	Surface drip	29	420	4.14	9
	Reduction (%)	*91.4*	*90.5*	–	*83.3*
5 August (49°C; RH 21%)	Waterlow®	2.5	42	3.57	1.5
	Surface drip	36	540	4.00	11
	Reduction (%)	*93.1*	*92.2*	–	*86.4*

RH: relative humidity; air temperature and RH measured in the shade at about 14:00. Mean discharge = applied volume/duration. Reduction (%) = 100 × (drip − Waterlow®)/drip

3.2 Applied fertilizer solution

To reach the same moisture endpoint, 1.5 L of fertilizer solution was applied with Waterlow® on both dates, compared with 9 L and 11 L with surface drip (Table 1), i.e. 83.3% and 86.4% less. These values describe applied solution volumes; no tracer or nutrient measurement at depth was made.

3.3 Estimated wetted soil volume

The estimated wetted soil volume was 78,500 cm^3 with Waterlow® on both dates and 113,040–116,840 cm^3 with surface drip (Table 2). Per litre of applied water, the Waterlow® event wetted about 31,400 cm^3 of soil, against 3,200–3,900 cm^3 for drip. Dividing applied water by wetted volume gives a mean increase in volumetric water content of 3.2% for Waterlow® and 25.7–30.8% for surface drip within the delineated zones.

Table 2
Dimensions and estimated volume of the wetted zone (20–60 cm depth) at the 60 cm sensor endpoint

Date	System	r (cm)[a]	h (cm)[a]	V_w (cm^3)	V_w per litre (cm^3 L^{-1})	Mean Δθ (% vol)[b]
29 June	Waterlow®	25	40	78,500	31,400	3.2
	Surface drip	30	40	113,040	3,898	25.7
5 August	Waterlow®	25	40	78,500	31,400	3.2
	Surface drip	30.5	40	116,840	3,246	30.8

$V_w = \pi r^2 h$ ($\pi = 3.14$). [a] Wetted radius (r) and vertical extent (h) measured in the field Radius and height were back-calculated from the reported volumes; please confirm with field measurements before submission. [b] Applied water/V_w, i.e. the mean increase in volumetric water content if all applied water had remained in the delineated zone

4 Discussion

4.1 Why Waterlow® reached 60 cm with less water

The main difference between the systems is the depth at which water enters the soil. With surface drip, the wetting front must cross the whole 0–60 cm profile, wetting the surface layer and spreading laterally in the coarse-textured soil before reaching the sensor. With Waterlow®, water is released at about 30 cm, so the front only had to travel about half that distance. In coarse-textured soils, wetting patterns from buried point sources tend to be elongated downwards, with most of the water moving below the emitter (Cote et al. 2003); this favours rapid arrival at depth. The endpoint used here therefore reflects both the delivery mode and this shorter travel distance; it should not be read as an equivalent irrigation outcome for the two systems.

The implied water-content increases support this interpretation. For drip, 25.7–30.8% by volume is high for a loamy sand and suggests that a large part of the applied water was stored in the 0–20 cm layer (excluded from V_w), moved beyond the delineated boundary, or evaporated from the wet surface during the 7–9 h tests (Allen et al. 1998; Kool et al. 2014). For Waterlow®, the 3.2% increase is low and suggests that the sensor responded once a wetting front had passed, before the whole delineated cylinder was uniformly wetted, possibly helped by flow along the injector and its pouch. In both cases the 60 cm endpoint is a front-arrival indicator, not a measure of stored water. The higher drip requirement in August (36 vs 29 L) is consistent with greater evaporative demand (49°C, 21% RH), while Waterlow® volumes did not change; however, initial moisture and discharge also differed slightly between dates, and evaporation was not measured.

These observations are consistent with the principle of direct root-zone delivery reported for grapevines, where water released at 30–90 cm reduced surface wetting and allowed lower irrigation rates (Ma et al.

2019, 2020), and with studies of buried clay pots and porous pipes (Bainbridge 2001; Siyal and Skaggs 2009). They also agree with SDI studies in date palm (Al Wahaibi et al. 2018; Alnaim et al. 2022; Bourziza et al. 2017). Nevertheless, those studies report seasonal outcomes (yield, water productivity), which cannot be compared directly with the single-event wetting volumes measured here. Published date palm water productivity values for Tunisian oases (Dhaouadi et al. 2017, 2022b; Tiba et al. 2025) provide context, but this experiment did not measure yield or seasonal irrigation and cannot estimate water productivity.

4.2 Fertilizer solution and irrigation time

Less fertilizer solution was applied with Waterlow® (1.5 vs 9–11 L) to reach the moisture endpoint, which suggests that root-zone delivery could reduce the volume of solution needed to place nutrients at depth. However, nutrient arrival and uptake at 60 cm were not measured. Similarly, irrigation duration was 90–92% shorter, but because both systems had similar discharges, this simply mirrors the volume difference. In pressurized systems, shorter irrigation could reduce pumping time, but energy savings require measurements of discharge, pressure and power under real operating conditions.

4.3 Practical considerations: clogging, roots and salinity

Root intrusion and emitter clogging are known risks of buried irrigation (Camp 1998; Lamm et al. 2012). Roots grow towards wetter soil (Eapen et al. 2005), so a permanently wet zone around the injector may attract roots; the fabric pouch is designed to limit intrusion, but its long-term performance in oasis conditions remains to be tested. Salinity is a key constraint in southern Tunisian oases (Marlet et al. 2009; Zammouri et al. 2007), and date palm yield decreases as soil salinity rises (Tripler et al. 2011). With buried point sources, salts may accumulate at the upper edge and between wetting zones, as observed under SDI with saline water (Hanson et al. 2008). Since electrical conductivity, drainage and groundwater level were not measured, this study cannot establish whether Waterlow® reduces or increases salt accumulation. In other installations, the developer uses four to five injectors per palm (Waterlow 2026); the number and spacing of injectors should be tested according to palm age, root distribution and soil texture.

4.4 Limitations and perspectives

This was a preliminary comparison on one palm, on two dates, without replication. The sensor was not calibrated and the endpoint threshold was defined on the instrument scale. The hydraulic head decreased during each test, wetted volumes were estimated geometrically, and the two outlets were at different depths relative to the sensor. Evaporation, nutrient concentration at depth, energy use, crop response and seasonal soil water and salt balances were not measured. Future work should (i) replicate treatments on several palms in a randomized design; (ii) use soil-calibrated moisture sensors at several depths and distances (Adla et al. 2020; Placidi et al. 2020); (iii) apply the same seasonal irrigation depth based on crop water requirements (Al-Muaini et al. 2019; Allen et al. 1998) and compare yield, fruit quality and water productivity; (iv) monitor soil salinity profiles and drainage; and (v) evaluate clogging, root intrusion and installation and maintenance costs.

5 Conclusions

Under two extreme summer conditions in Douz (41°C and 49°C), a Waterlow® root-zone injector needed 2.5 L of water and 40–42 min to trigger a sensor response at 60 cm depth in a loamy sand soil, compared with 29–36 L and 7–9 h for a surface dripper with a similar discharge. Smaller volumes of fertilizer solution were also applied to the same endpoint. These results show that releasing water below the surface strongly changes the wetting pathway and limits wetting of the upper soil layer. They do not yet quantify seasonal water or fertilizer savings, energy savings, yield effects or long-term salinity outcomes. Replicated, season-long trials with calibrated sensors and water–salt balances are needed before the system can be recommended on the basis of quantified resource savings.

Declarations

Author Contribution

H.B. and N.N. to the study methodology, conducted the field experiments and collected the data . L.D. contributed to data analysis, interpretation of results, and preparation of the manuscript. H.B. and L.D. wrote and revised the manuscript. All authors reviewed and approved the final version of the manuscript.

Data Availability

The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

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Figures



Figure 1

Waterlow® injectors before installation, showing the vertical tube, the HDPE cap with air inlet, the lateral fittings and the non-woven fabric pouch at the lower end

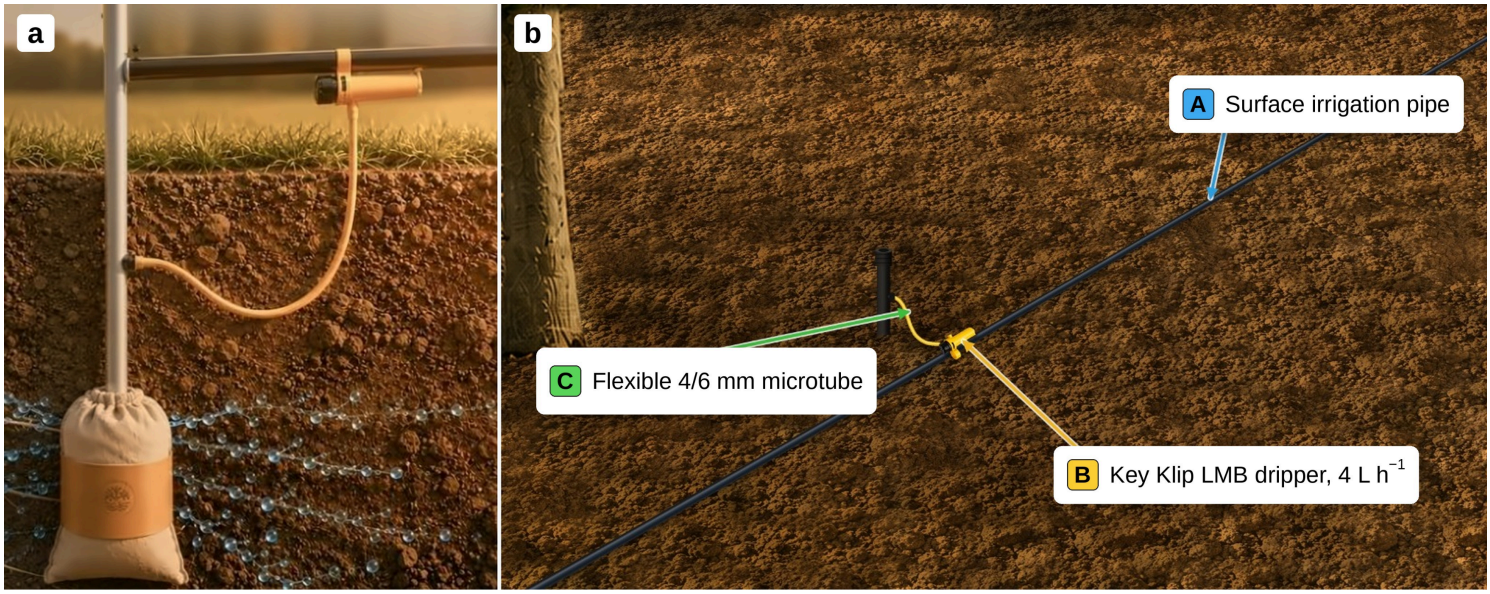

Figure 2

Waterlow® installation: (**a**) schematic illustration of an installed injector (not to scale); (**b**) connection system — (A) surface irrigation pipe, (B) Key Klip LMB 4 L h^{-1} dripper, (C) flexible 4/6 mm microtube connected to the injector