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ORIGINAL PAPER

Mitigating soil water deficit using organic waste compost and commercial water retainer: a comparative study under semiarid conditions

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Abstract

Semiarid regions have particularly been confronted with climate change effects reflected by the consistent decrease of rainfall and increase of evapotranspiration. This drought stress constitutes the main constraint for agricultural production improvement, which is aggravated by the fact that strategic (field) crops are mostly grown under rainfed systems. Therefore, the objective of this field study was to improve soil water retention by the application of two conditioners namely, an organic waste compost (DS) and a synthetic water-retaining hydrogel (WS). These amendments were applied to an agricultural soil for the cultivation of fodder maize under normal and deficit irrigation regimes. Advanced analysis showed a general disruption of plant growth parameters under water stress. However, both amendments attenuated this negative effect with respect to control by improving soil water status. More precisely, the measured soil water tension at the start of the dry season was the lowest in presence of DS (48 centibars), followed by WS (61 centibars), then unamended soil (83 centibars). Besides, compost application resulted in higher moisture (13.3%), nitrogen (0.36%), and organic matter (0.56%) in soil than the synthetic hydrogel at the end of the field experiment. Soil and plant characterization highlighted the combined effect of water deficit and conditioner type. Indeed, the consistent increase of soil water content in the presence of DS and WS improved all the addressed plant parameters when compared with untreated soil. Infrared thermal imaging showed that canopy temperature was lower in presence of both amendments while dry biomass yield increased by 38% when water supply was limited. Nevertheless, the long-term sustainability of the soil system appears to be better maintained in the presence of the organic waste compost. The latter has the added advantage of improving soil fertility in contrast to inert polymers.

Keywords Deficit irrigation · Water tension · Soil conditioners · Plant growth · Soil fertility

Introduction

Climate change has led to extreme temperatures and rainfall deficiency, which provides a perfect storm for a new epoch of environmental crises and agronomic potentiality. Water scarcity is a serious global issue and thus needs to be linked with the United Nations (UN) Sustainable Goals as well as the 2030 Farm-to-Fork EU strategy (Vanham and Mekonnen 2021). In particular, semiarid regions are the least endowed in terms of fresh water resources, amplified by climate change forecasts and unpredictability of annual rainfall (Radhouane 2018). As a living example, the temperature in the Mediterranean basin has been rising 25% faster than the rest of the globe (Alrteimei et al. 2022). These climatic constraints have severely affected soil conditions and ultimately crop production in most drought-prone countries (Leng and Hall 2019). For instance, the season 2022–2023 was

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extremely dry in Tunisia, which resulted in water shortages in major dams with a national storage rate of only 27.3% as of September 2023. This has pushed local authorities to ration irrigation and drinking water supplies (Reuters 2023).

To cope with these restrictive conditions, some practical solutions have been proposed to efficiently manage the scarce water resources and promote land use, such as the reduction of water losses, using more efficient irrigation techniques (Mahdhi et al. 2019) and the enhancement of soil properties for better water retention (Zekry et al. 2020). In this regard, the incorporation of organic waste materials such as animal manure, crop residues, composts, and sludge has historically been the most recommended and environmentally friendly practice advocated by farmers for soil enhancement (Alotaibi and Schoenau 2019; Hamdi et al 2019; Rodríguez-Espinosa et al. 2023a, b). This integrated organic waste recycling approach improves the physical properties of soils such as the structural stability and water-holding capacity, which reduces leaching below the rooting zone (Bortolotti et al. 2018; Zoghlami et al. 2020). In addition, the microbial degradation of the incorporated organic matter is a slow-release process for macro- and micronutrients to agricultural plants (Hadroug et al. 2021; Mabrouk et al. 2023). Simultaneously, this could significantly reduce the emission of greenhouse gases in case of organic waste landfilling (Christodoulou et al. 2019; Huang et al. 2022).

The composting of organic wastes has been of particular interest in terms of sustainable waste management and soil enrichment with stabilized materials rich in nutrients and beneficial microorganisms (Waqas et al. 2023). In this regard, Martínez-Blanco et al. (2013) identified a total of nine agroenvironmental benefits of organic waste composts in an extensive literature review that were classified into short-, mid-, and long-term. These include primarily improved nutrient supply, carbon sequestration, moisture retention, and decreased soil erosion. To achieve such goals, composting requires appropriate feedstock mixtures that contain moisture, nutrients, a balance of C:N ratio, a consistency that facilitates both rapid decomposition (maturation) and air movement, and a minimum of contamination (Oshins et al. 2022; Chen et al. 2023). Several cropping trials have evidenced the positive effect of compost on the soil–plant system. Wolka and Melaku (2015) reported high maize yield in plots treated with compost prepared by mixing 50% food waste with 50% cattle manure compared with the control or other feedstock mixing ratios. Mixing food waste compost with livestock manure compost in the right proportion produced higher lettuce yield and better soil conditions than single compost amendments or chemical fertilizers (Yang et al. 2020). A specific objective sought from compost reuse in water-stressed regions is the improvement of soil water-holding capacity (WHC) regardless of possible influence of soil type and crop species (Abd El-Mageed et al. 2019).

In recent years, several synthetic soil conditioners have been developed and marketed for the main purpose of the fast improvement of water retention capacity (Saha et al. 2020). Among these products, super-absorbent polymers present very high retention capacity originating from the hydrophilic functional groups attached to the backbone of the polymer. These absorbers can have a capacity of water retention up to 1000 times their original weight (Mignon et al. 2019). Besides, there are also super absorbent hydrogels composed of insoluble materials forming three-dimensional networks that swell and retain large amounts of water due to their cross-links (Rivera Fernández et al. 2018). Once incorporated into the soil, these super absorbents can quickly retain moisture by acting as water traps then subsequently release it into the root zone. In particular, this water retention capacity is very important during the critical growth stages of crops that coincide with the onset of drought periods (Al-jabari et al. 2019). Accordingly, Kargar et al. (2017) and AbdAllah et al. (2021) indicated that these highly absorbing materials are effective in increasing soil WHC and decreasing deep percolation, which improves crop growth and productivity. For instance, Robiul Islam et al. (2011) observed a superior corn growth and water use efficiency in the presence of a super-absorbent polymer under deficit irrigation. They ascribed that to the maintenance of higher relative water contents in leaves, as well as higher intercellular carbon dioxide concentration, net photosynthesis, and transpiration rate.

As previously mentioned, several studies have investigated the effect of organic waste composts and commercial water-retaining polymers on maintaining soil moisture, but mixed outcomes have been published on the performance of each soil conditioner. This depends largely on the properties of added materials as well as the edaphic-climatic factors and cultivation conditions specific to each region of study. On these grounds, the present research work aimed to propose an efficient and sustainable solution to improve water retention under semiarid stress conditions by comparing the performance of two different soil conditioners. More precisely, soil water tension was regularly monitored for 80 days after amendment with an organic waste compost and a commercial water retainer to investigate their efficiencies in terms of improving fodder maize growth under normal or deficit irrigation.

Materials and methods

Study site

The crop field trials were carried out during the spring of 2021 (08 March 2021–27 May 2021) at an agricultural research station belonging to the National Institute

Fig. 1 Location of the experimental site within Tunisia and the Mediterranean basin

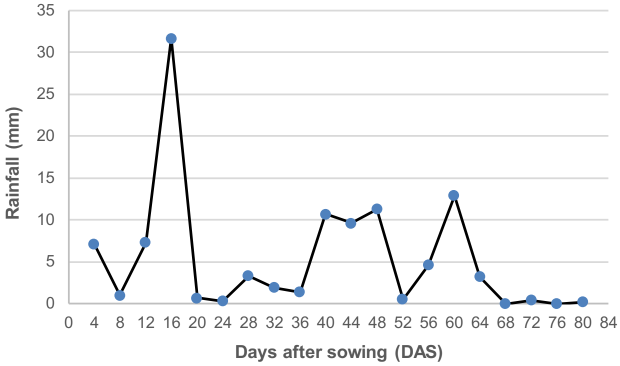

Fig. 2 Variation of rainfall as cumulative 4-day amounts in mm starting from seed sowing date until the end of cultivation process

of Agricultural Research of Tunisia (INRAT), located in Northern Tunisia (36° 51′ 45″ N, 10° 11′ 44″ E) (Fig. 1). The region is characterized by a typical south Mediterranean semiarid climate with relatively mild and rainy winters and prolonged hot and dry summers. Average annual rainfall ranges between 350 and 400 mm but is highly unpredictable and varies largely in time. Meteorological data throughout the study period were retrieved from an automatic meteorological station (Delta-T Devices Ltd, Cambridge, UK) implemented close to the experimental site. The total rainfall registered during the field study was 108.1 mm (Fig. 2). The mean temperatures varied between 7.8 and 26.7 °C with daily maxima often exceeding 30 °C towards the end of cultivation cycle (up to 35.6 °C) (data not shown).

Properties of agricultural inputs

Experimental soil

Prior to starting cultivation trials, topsoil samples (0–30 cm) were randomly collected from the experimental field and bulked out. Collected soil samples were oven-dried at 105 °C and sieved through 2-mm mesh for major physical and chemical characterization. The agricultural soil is clay loam, with a high sand fraction (36%) typical for the study region (Table 1). The organic matter (OM) and nutrient contents were low, which characterizes the depleted semi-arid agricultural soils of the south Mediterranean region

Table 1 Physicochemical properties of the experimental soil and organic waste compost

	Sand (%)	Silt (%)	Clay (%)	pH	EC (dS m^{-1})	TOC (%)	OM (%)	TN (%)	C:N	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
Soil	36	34	30	8.12	1.1	0.3	0.52	0.11	2.7	3.39	7.75	1.16
Compost	–	–	–	6.9	12	23	39.5	1.37	14.6	67	300	30

(Table 1). This was also evidenced by the slight alkalinity (8.12) and salinity (1.1 dS m^{-1}).

Organic waste compost

The compost consisted of a 1-year mature compost prepared from the aerobic decomposition of a mixture of fresh market vegetable wastes and sheep manure. The composting process was carried out at the composting unit of the Technical Center for Organic Agriculture (CTAB, Chott-Meriam, Tunisia) as a sustainable waste management option to prevent landfilling issues. Some properties of the used compost are presented in Table 1. With a C:N ratio of 14.6 (<20), this organic matter-rich compost was considered finished, stable and suitable for land application. The high electrical conductivity (EC) value of 12 dS m^{-1} is a general characteristic of organic amendments made from animal manures (Al-Turki et al. 2013).

Commercial soil conditioner

The soil-conditioning product used in this study is sold under the commercial name of Water Retainer® and saves up to 30% of water with a 3-month effect after application according to the manufacturer's catalog (Water & Soil Ltd., Hungary). It is a hygroscopic product sold in a liquid form that can be mixed with irrigation water or sprayed directly onto the soil surface close to the root zone. Its mode of action is to entrap part of the humidity (water) that evaporates through the soil capillary system as well as air humidity making more water available to plants than untreated soil.

Experimental design

The experimental field was ploughed to a depth of 45 cm followed by two recrossing passages with a rotary cultivator to prepare the seedbed in January 2021. To investigate the performance of both soil amendments in improving water status under semiarid field conditions, six soil treatments were implemented corresponding to combinations of three cultivation substrates and two water regimes (Table 2). The cultivation substrates were: (1) unamended soil control (named inert substrate, IS), (2) soil mixed with organic waste compost (named Dynamic Substrate, DS), and (3) soil treated with synthetic water-retaining substrate (named WS). Two irrigation regimes were deployed in this experiment for each soil treatment: (1) normal irrigation (N, 20 L m^{-2} per irrigation) corresponding to the full water requirement of fodder maize crop, and (2) deficit irrigation (D, 50% of N dose). The field trials were carried out in a randomized complete block design with three replicates per treatment distributed in three blocks (Fig. 3). As such, each block was divided into six treatment plots of 6 m^2 each separated by a border zone to prevent water leaking. Irrigation was carried out using a microsprinkler system placed in each plot. Compost was incorporated into the topsoil at the rate of 2 kg m^{-2} before seed sowing while the water retainer was pulverized onto the soil surface at a final volume of 100 mL per m^2 (4%) after seed sowing.

Eighteen seeds of fodder maize (*Zea mays* L., var. Kolosseus) were sown manually in each plot on 08 March 2021. The plant spacing was 25 cm, row spacing was 50 cm, and the sowing depth was 4 cm. For all treatments, the irrigation was performed two to three times per week with normal (N) or deficient (D) water doses supplied during early morning time. Chemical fertilization with NPK was performed for all treatments according to the local guidelines for fodder maize cultivation. The field study lasted for 80 days after sowing (DAS), which corresponds to the stage of the first green fodder cutting (Rathod and Dixit 2019).

Soil moisture monitoring

Throughout the course of cultivation, soil water tension (SWT) was monitored every 4 days during morning time using tensiometer probes installed in the center of each plot at 50 cm depth (Watermark 200SS; IRROMETER Co., Riverside, CA). Probes are equipped with granular matrix

Table 2 Treatment combinations of irrigation regimes and soil conditions

Treatments		1 factor	2 factor	
		Irrigation (2–3 times/week)	Compost (incorporated before seed sowing)	Water retainer (sprayed after seed sowing at 4%)
1	N-IS: normal irrigation	20 L m^{-2}	–	–
2	D-IS: deficit irrigation	10 L m^{-2}	–	–
3	N-DS: normal irrigation with compost	20 L m^{-2}	2 kg m^{-2}	–
4	D-DS: deficit irrigation with compost	10 L m^{-2}	2 kg m^{-2}	–
5	N-WS: normal irrigation with water retainer	20 L m^{-2}	–	100 mL m^{-2}
6	D-WS: deficit irrigation with water retainer	10 L m^{-2}	–	100 mL m^{-2}

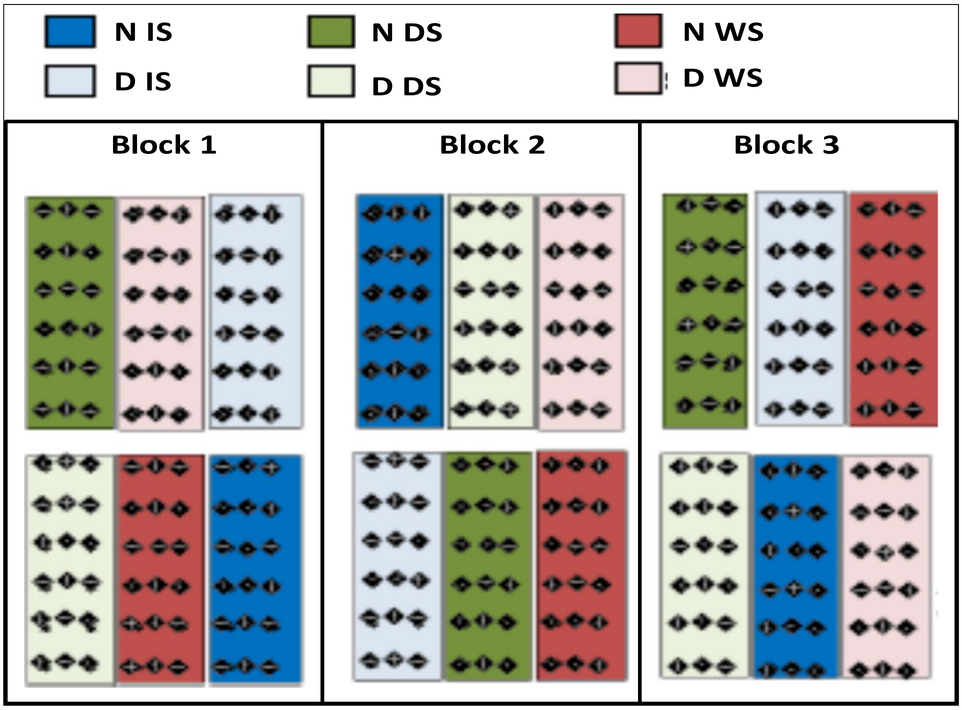

Fig. 3 Randomized distribution of treatment combinations. *N* normal irrigation, *D* deficit irrigation. *IS* control (unamended) soil, *DS* soil amended with organic waste compost, *WS* soil treated with commercial water retainer

sensors that indirectly measure the moisture potential of the soil using electrical resistance. Values range from 0 to 10 centibars (saturated soils), from 10 to 100 centibars (usual range of irrigation according to soil texture), and from 100 to 200 centibars (dry soils), which reflect the variations of the water tension in the soil (Qazi 2020). Simultaneously, the actual soil water content (SWC) at the same depth and time was determined by calculating the difference between the soil fresh weight (SFW) and soil dry weight (SDW), after drying soil samples for 48 h at 105 °C (Eq. 1) (Rabat et al. 2016).

$$\mathrm{SWC}\,(\%) = \frac{\mathrm{SFW} - \mathrm{SDW}}{\mathrm{SDW}} \times 100 \qquad (1)$$

At the end of the cultivation period (80 DAS), irrigation was ceased and different soil and plant parameters were measured to highlight the combined effect of the applied treatments. The focus was mainly on comparing the performance of both amendments (DS and WS) in improving the soil water status under deficit irrigation.

Soil physicochemical properties

Soil samples were taken from all replicate plots at 50 cm depth in three representative diagonal points. Samples were composited, dried then sieved through 2-mm mesh for subsequent analysis using standard methods. Concentrations of Ca and Mg were measured using the EDTA titration method. Potassium content was assessed by flame photometry. Soil pH and electrical conductivity (EC) were measured in a 1:5 soil–water suspension. Kjeldahl and Walkley–Black wet oxidation methods were used to determine total N (TN) and total organic carbon (TOC), respectively.

Plant properties

Total chlorophyll content

The chlorophyll content in maize leaves was determined in situ using a Konica Minolta SPAD-502 portable chlorophyll meter. Readings were made on the same fully expanded leaf close to midrib for 10 random plants in each plot (Dong et al. 2019). SPAD readings are automatically calculated based on the difference between two transmission values: the transmission of red light at 650 nm, which is absorbed by chlorophyll, and the transmission of infrared light at 940 nm, at which no chlorophyll absorption occurs (Hosoi et al. 2019).

Growth parameters

Canopy height (CH) and stem height (SH) of maize plants were measured with a ruler at three randomly selected points within each replicate plot, with an average of these heights recorded to provide a representative value. Above-ground and root biomasses were collected from individual plots, bundled, dried at 105 °C for 1 week, then weighed to obtain shoot and root dry weights (SDW and RDW). Leaf number (LN) and total leaf surface area (LSA) was measured by a Leaf Area Meter (CID Inc., USA). Leaf area index (LAI) was then calculated as the proportion of leaf area per unit of land area.

Leaf water status

Leaf relative water content (LRWC) was estimated using the method of Sun et al. (2019). Three discs samples (6 cm^2) from the fully expanded leaf were taken using a puncher to determine the fresh weight (LFW). The samples were then immerged in distilled water for 24 h to regain full turgor (LTW) and placed in an oven at a temperature of 105 °C until a constant dry weight was obtained (LDW). LRWC was calculated as following (Eq. 2):

$$\mathrm{LRWC}\,(\%) = \frac{\mathrm{LFW} - \mathrm{LDW}}{\mathrm{LTW} - \mathrm{LDW}} \times 100 \tag{2}$$

Normalized difference vegetation index (NDVI)

The normalized difference vegetation index (NDVI) was estimated using FieldScout® CM 1000 NDVI-meter (Kargar et al. 2017). For this experiment, ten measurements were taken for each replicate plot at approximately 0.5 m above the plant canopy during the morning time (10:00 am to 12:00 pm). NDVI was then calculated according to Babar et al. (2006) (Eq. 3):

$$\mathrm{NDVI} = \frac{\%\mathrm{NIR} - \%\mathrm{R}}{\%\mathrm{NIR} - \%\mathrm{R}} \tag{3}$$

where, NIR and R are reflectances in the spectral range of the near infrared and red, respectively.

Acquisition of infrared thermal images (IRT)

Thermal images were also taken at the stage of 80 DAS on the sunny parts of seven seedlings for each treatment. Infrared thermal images (IRT) were acquired with an infrared camera (model FLIR C3 system, Inc., Wilsonville, OR). Each image was obtained from a constant distance of 1 m perpendicular to the row direction. Thermal images were taken during a calm day, which prevents the influence of air movement on temperature variability within the canopy and reference leaves. Thermal images were processed using FLIR tools software (version 2.0, FLIR system, Inc. Wilsonville). To exclude nonleaf material from analysis, areas of different shapes in each image were manually selected, and the average temperature of each area was used to calculate canopy temperature (CT) (Grant et al. 2007). Simultaneously, soil surface temperature (ST) was also determined.

For each treatment, the reference surface temperatures (T_{dry} and T_{wet}), which represent respectively the maximum and minimum temperatures of a non-transpiring leaf (dry) or a fully transpiring leaf (wet), were also obtained simultaneously with the acquisition of infrared thermal images (Jones 2004). The reference surface temperatures were taken on nondetached mature and representative leaves from a reference plant. T_{dry} and T_{wet} transpiration conditions were simulated by painting both leaf surfaces with liquid petroleum jelly (Vaseline) and water + detergent, respectively (Salgadoe et al. 2019). The thermal indices namely, crop water stress index (CWSI) (Eq. 4) and stomatal conductance index (GI) (Eq. 5) were calculated using the equations proposed by Jones (2004) as follows:

$$\mathrm{CWSI} = \frac{\mathrm{Tcanopy} - \mathrm{Twet}}{\mathrm{Tdry} - \mathrm{Twet}} \tag{4}$$

$$\mathrm{GI} = \frac{\mathrm{Tdry} - \mathrm{Tcanopy}}{\mathrm{Tcanopy} - \mathrm{Twet}} \tag{5}$$

Statistical analysis

The dependent variables were subjected to analysis of variance (ANOVA) using the MIXED procedure of the SAS 9.0 software (SAS Institute Inc., NC). The test for the least significant difference Fisher's protected (LSD) was used for multiple comparisons of treatments using LSMEANS of SAS 9.0. Conversion to letter groupings was obtained by SAS macro pdmix800. The separations of means were significant at $P \leq 0.05$. The strength of relationship between different parameters was estimated using Pearson product–moment correlation coefficients (r) at $P \leq 0.05$.

Results and discussion

Effect of treatments on soil properties

In this study, soil water tension was measured every 4 days at 50-cm depth throughout the field trial (March 2021 through May 2021). The relationship with soil water content from actual soil samples taken simultaneously from all treatments is shown in Fig. 4. There was a significant negative linear correlation between both parameters ($R^2 = 0.95$) for the data range obtained during the field investigation. Accordingly, when soil moisture increases from 10 to 25%, SWT decreases linearly from 70 to nearly 15 centibars. Therefore, water availability and the ability of the soil to store water and act as a reservoir for plants depend on the tension (force) exerted by the soil to retain water and to release it subsequently. In this study, the relationship between these two soil attributes is represented by a linear function called soil water characteristic (Or and Wraith 2002). Accordingly, water storage in soil depends largely on soil physical properties

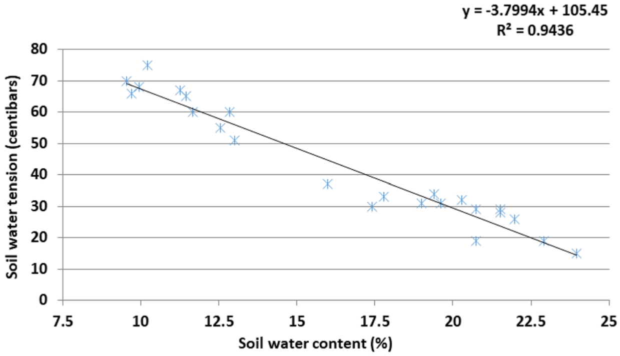

Fig. 4 Relationship between soil water tension (SWT) and the soil water content (SWC) during the course of fodder maize cultivation. The best-fit equation and its regression coefficient are herewith shown

such as texture, porosity, structural stability, and organic matter content (Or and Wraith 2002; Zoghlami et al. 2020).

On the other hand, results showed that the variation of soil moisture (inversely reflected by SWT) was influenced by the applied treatment and climatic conditions depending on the rainfall event and irrigation supply (Fig. 5). Throughout the experimental period, a higher SWT was consistently observed when deficit irrigation was applied independently of the substrate type (D treatments). Soil water tensions were in the range of 20–40 centibars under normal irrigation but exceeded 80 centibars under deficit irrigation (Fig. 5). According to the manufacturer's manual, soil readings of 30–60 centibars represent a usual range of most irrigated soils while readings between 60 and 100 centibars indicate on water status in irrigated heavy clay soils (less accessible to plants due to stronger retention). Significant drops in SWT were nevertheless noticed in deficit-irrigated treatments at some dates, approaching those conducted under normal irrigation regime. This coincided with rainfall events where all plots received the same amount of rain that masked the effect of irrigation regime variation (Fig. 2). On the other hand, a substantial increase in SWT was observed for deficit-irrigated treatments starting from 64 DAS, which corresponded to the end of the mild season and the onset of hot and dry conditions in the region of study at the beginning of May (Fig. 2). Kumar et al. (2017) made the same observations and attributed the higher SWT to deficit irrigations coupled to excessive evaporation rates when air becomes dryer.

The variation of SWT under both irrigation regimes was consistently lower for DS and WS than IS substrate throughout the course of fodder maize cultivation process. As shown in Fig. 4, this variation was more pronounced in deficit irrigation treatments especially with the onset of the dry season (starting from 64 DAS). For instance, measurements taken at 68 DAS showed SWT values of 28, 31 and 38 centibars for N-DS, N-WS, and N-IS, respectively; 48, 61, and 83 centibars for D-DS, D-WS, and D-IS, respectively. Accordingly, soil amendments improved soil water retention by reducing losses due to infiltration and evaporation as compared with unamended soil treatments (Luna et al. 2018). This effect was, nevertheless, attenuated when irrigation was not deficient as testifies the narrower variation of SWT in N-DS, N-WS, and N-IS at the end of cultivation cycle (26.3–31.3 centibars) (Fig. 5). Unamended soil can intrinsically retain water and show low tensions when water supply is sufficient and the water-absorbing clay fraction is representative as is the case in this study (Hechmi et al. 2020; Wang et al. 2021). On the other hand, the organic waste compost added at a rate of 2 kg m^{-2} resulted in higher soil water content as compared with sprayed commercial hydrogel and unamended soil for both irrigation regimes. Under water deficit, compost addition significantly reduced SWT by 42% when compared with untreated soil at 80 DAS (Fig. 5). Consequently, concurrently measured SWC values were 13.3% and 8.9% for D-DS and D-IS, respectively (Table 3).

The used compost made from vegetable wastes and sheep manure had a substantial content of OM (~40%) as illustrated in Table 1. This was reflected by a higher OM content in D-DS treatment at the end of cultivation trial

Fig. 5 Variation of soil water tension (SWT) in all treatments until 80 days after sowing (DAS). *N* normal irrigation, *D* deficit irrigation. *IS* control (unamended) soil. *DS* soil amended with organic waste compost. *WS* soil treated with commercial water retainer

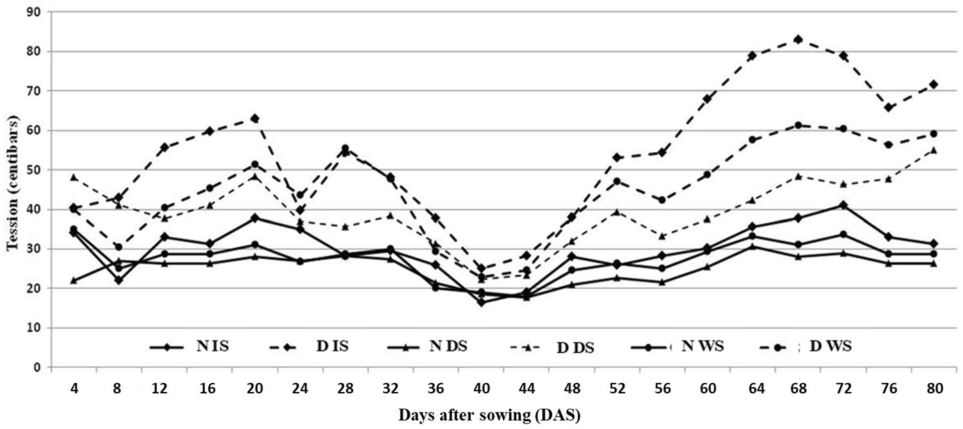

Table 3 Effect of treatments on soil physicochemical properties under deficit irrigation at the end of the field study

Treatment	SWC (%)	OM (%)	TN (%)	pH	EC (dS m^{-1})
D-IS	8.9 ± 0.8^{a}	0.44 ± 0.03^{a}	0.21 ± 0.01^{a}	6.83 ± 0.2^{a}	1.74 ± 0.01^{a}
D-WS	12.2 ± 1^{a}	0.44 ± 0.02^{a}	0.24 ± 0.01^{a}	7.57 ± 0.2^{b}	1.76 ± 0.01^{a}
D-DS	13.3 ± 1.5^{a}	0.56 ± 0.04^{b}	0.36 ± 0.02^{b}	7.61 ± 0.3^{b}	1.90 ± 0.02^{b}

Values are means of triplicate ± standard errors (SE). Means in the same column followed by superscript letters in common are not significantly different at $P \leq 0.05$

SWC soil water content, *OM* organic matter, *TN* total nitrogen

(Table 3). The increase of OM content in soil has always been accompanied by an improvement of its water-holding capacity (Luna et al. 2018). Organic matter is composed of negatively charged long carbon chains and hydrophilic sites that attract water molecules to adhere to the surface (Lal 2020). The water dynamic analyses also show that an important fraction of water molecules are confined between organic particles as well. In fact, the way these chains are tangled creates cavities (pores) and vacuum that can entrap water (Escalona et al. 2021). Depending on soil texture, a 1% increase in soil organic carbon can cause a 2% to more than 5% increase in soil water-holding capacity (Olness and Archer 2005). Reicosky et al. (1995) indicated that certain types of soil organic matter could hold up to 20 times their weight in water. Organic matter addition improves soil physical properties mainly the number of micropores either by "gluing" soil particles together (clay–humus complexes), which increases WHC as well. For instance, Widowati et al. (2020) found that the addition of municipal compost significantly increased soil porosity with respect to unamended soil from 41.2–45.1% to 52.1–61.4% depending on soil texture. Moreover, by incorporating a commercial compost at 3%, Kogbara et al. (2020) also noticed an increase in cumulative porosity as compared with unamended soil (50% versus 42%, respectively) during alfalfa cultivation under extreme arid conditions. Besides, Ali (2011) observed a decrease in soil bulk density as well as macroporosity (drainage pores) in favor of micropores and WHC when rice straw compost or synthetic cellulose polymer were added to a sandy soil. In our current study, the addition of compost increased soil water content as it was reflected by least SWT values under both watering regimes during the whole course of cultivation process (Fig. 5).

The commercial liquid water retainer, sprayed onto the soil surface at 4% concentration for a dose of 100 mL m^{-2}, improved water retention as well by consistently showing lower SWT than control soil under both irrigation regimes. As for compost, the positive effect was more pronounced when irrigation was deficient (Fig. 5). Accordingly, at the end of the field trial, there was a reduction of 26% in SWT when compared with unamended soil. This was reflected by an intermediate SWC of 12.2% as presented in Table 3. Most of commercial retainers are made of functional polymer materials with strong water absorption capacity (Yang et al. 2020). The manufacturer of the Water Retainer® used in this study does not disclose any details about its composition except its organic nature. Organic polymer materials are largely classified into natural biodegradable and synthetic nontoxic biodegradable polymers. For improved performance of the pristine organic polymers, their natural structures can be altered using enzymes, chemicals, and thermal treatment. For instance, Rullyani et al. (2018) reported that natural and synthetic organic polymers such as chitosan and polyaniline, respectively, are nontoxic, biocompatible, chemically stable, and environmentally benign water absorbents. As it is sold in a liquid form, the current product is most likely a hydrogel, which is a water-containing gel made from three-dimensional (3D) networks of polymers. Regardless to the applied form, the positive effect of synthetic conditioners on soil water retention has previously been reported under various conditions (Al-Jabari et al. 2019; Zekry et al. 2020). Polymers have been reported to improve soil physical properties, retain irrigation and rainwater, and help to reduce deep percolation by absorbing gravitational water as well as capillary water. More precisely, water can be trapped into the water-retaining polymer by osmosis or by binding with hydrogen bonding (Chang et al. 2021). In any case, the SWT study carried throughout the course of maize cultivation significantly highlighted the importance of both amendments in decreasing water stress in case of insufficient supply when compared with unamended soil. However, the commercial water retainer did not improve OM content in soil, as did the organic waste compost, which could have repercussions on the sustainability of water retention in soil systems (Table 3). In this regard, the user's manual clearly stipulates that it has only a 3-month effect after application, which corresponds roughly to the actual experimental period of this research study.

Effect of soil treatments on maize agromorphological properties

As with the variation of soil water conditions, the adopted treatments strongly affected the agromorphological characteristics of maize plants measured at the end of the cultivation cycle (Table 4). In general, the normal irrigation regime

Table 4 Effect of different soil treatments on biomass and morphology of fodder maize plants at the end of the field study

	LRWC (%)	LSA (cm^2)	LAI	LN	CH (cm)	SH (cm)	LDW (g)	RDW (g)	SDW (g)
Normal irrigation									
N-IS	61 ± 5.3^{a}	1368 ± 204^{a}	1.50 ± 0.27^{a}	9.6 ± 0.47^{a}	77.3 ± 5.6^{bc}	38.6 ± 6.7^{a}	37.0 ± 5.6^{a}	19.2 ± 4.2^{a}	53.0 ± 14.8^{a}
N-WS	68 ± 4.7^{b}	2406 ± 204^{b}	2.33 ± 0.27^{b}	11.3 ± 0.47^{b}	97.0 ± 5.6^{d}	74.3 ± 6.7^{b}	65.0 ± 5.6^{b}	35.3 ± 4.2^{b}	155.0 ± 14.8^{c}
N-DS	64 ± 5.3^{ab}	1694 ± 204^{a}	1.66 ± 0.27^{ab}	11.0 ± 0.47^{ab}	83.3 ± 5.6^{cd}	61.6 ± 6.7^{ab}	45.6 ± 5.6^{a}	20.3 ± 4.2^{a}	88.3 ± 14.8^{bc}
Deficit irrigation									
D-IS	50 ± 7.3^{a}	1121 ± 204^{a}	1.00 ± 0.27^{a}	8.0 ± 0.47^{a}	59.0 ± 5.6^{a}	27.6 ± 6.7^{a}	31.0 ± 5.6^{a}	9.6 ± 4.2^{a}	43.6 ± 14.8^{a}
D-WS	56 ± 4.5^{a}	1195 ± 204^{a}	1.33 ± 0.27^{a}	9.6 ± 0.47^{a}	64.6 ± 5.6^{ab}	33.3 ± 6.7^{a}	32.6 ± 5.6^{a}	8.6 ± 4.2^{a}	68.8 ± 14.8^{ab}
D-DS	62 ± 5.8^{a}	1476 ± 204^{a}	1.33 ± 0.27^{a}	10.0 ± 0.47^{ab}	78.3 ± 5.6^{bc}	45.0 ± 6.7^{ab}	41.0 ± 5.6^{a}	9.5 ± 4.2^{a}	69.0 ± 14.8^{ab}

Values are means of triplicate ± standard errors (SE). Means in the same column followed by superscript letters in common are not significantly different at $P \leq 0.05$

LRWC leaf relative water content, *LSA* total leaf surface area, *LAI* leaf area index, *LN* leaf number, *CH* canopy height, *SH* stem height, *LDW* leaf dry weight, *RDW* root dry weight, *SDW* shoot dry weight

resulted in higher plant performance than did deficit irrigation. This can be highlighted when analogous soil treatments are compared two by two for all measured parameters (e.g. N-DS versus D-DS). Obviously, this improvement was strongly correlated to the water status in soil as reflected by consistently lower SWT values under normal irrigation throughout the 80 days of cultivation (Fig. 5). In this context, Liu et al. (2020) pointed out that "dryness stress" can limit vegetation growth and is often characterized by low soil moisture during high atmospheric water demand. In absence of any soil amendment, maize plants consistently showed the lowest variations under each irrigation regime group (Table 4). This reflects the importance of soil conditioners under any soil water status in enhancing plant growth by primarily increasing water accessibility to roots (Bortolotti et al. 2018; AbdAllah et al. 2021). In this study, the effect of both soil amendments was significantly influenced by the irrigation regime. While the addition of the commercial water retainer resulted generally in the most significant improvement of the agromorphological parameters under normal irrigation regime, the organic waste compost was more efficient when water supply was limited (Table 4). Ali (2011) also reported similar results for a sandy soil amended with rice straw compost compared with a synthetic cellulose polymer. In addition to external factors that may influence the effect of both amendments such as intrinsic quality and applied dose, the biostimulation and bioaugmentation effect of the organic waste compost as a bioactive material can significantly enhance soil biological activity when water supply is limited (Hamdi et al. 2007). Consequently, microbial extracellular polymeric substances released by certain cyanobacterial species can modify water retention by increasing WHC as observed in drylands by Adessi et al. (2018). Under normal irrigation, the commercial water retainer showed the highest plant performance that seems not strictly correlated to the water status in soil throughout the cultivation cycle as shown in Fig. 4. De Jesus Souza et al. (2016) noticed also a positive correlation between irrigation levels and coffee plant parameters in presence of a water-retaining polymer, with highest performance at 100% water supply. It appears that the water retainer performs better when soil moisture is high enough to induce the capacity of water slow release within the rhizosphere zone.

The leaf relative moisture content is considered one of the best growth indices revealing the intensity of water stress for a given plant species (Zhang et al. 2018). As previously mentioned for agromorphological parameters, plants grown on unamended soils showed consistently lower LRWC as compared with the rest of treatments (61% and 50% for N-IS and D-IS, respectively). Accordingly, water stress negatively affected LRWC in all treatments but at different levels (Table 4). When similar soil treatments are compared, there is about 18% decrease for plants grown on IS and WS substrates but LRWC is maintained at a higher level in presence of compost (only 4% decrease). Zhang et al. (2018) also observed LRWC values of only 62.7% and 49.8% after initiating water deficit for 3 and 6 days, respectively, in seedlings of a different maize cultivar. Under water stress, various LRWC levels have been reported for maize because these studies have been conducted under different pedoclimatic conditions and using different cultivars. Selection programs for cultivars may reflect the capacity for more efficient water uptake from moisture-deficient soils or the ability of stomata to reduce water loss for water conservation (Zhang et al. 2018; Langner et al. 2021). The maintenance of a higher LRWC ensures better hydration as shown in the study of Langner et al. (2021) who noticed more favorable water relations in internal tissues and better capacity for tolerance to drought in resistant plants. As presented in Table 5, all addressed agromorphological properties were highly correlated to LRWC, showing significant Pearson product-moment correlation coefficients varying between

Table 5 Matrix of Pearson product-moment correlation coefficients for soil and plant parameters

	SWT	LRWC	LSA	LAI	LN	CH	SH	LDW	RDW	SDW	SPAD	NDVI	GI	CWSI	CT	ST
SWT	–	*– 0.87*	*−0.71*	*−0.79*	*−0.83*	*−0.84*	*−0.78*	*−0.68*	*−0.80*	*−0.59*	*−0.87*	*−0.91*	*−0.94*	*0.92*	*0.92*	−0.03
LRWC		–	*0.86*	*0.97*	*0.95*	*0.97*	*0.91*	*0.88*	*0.85*	*0.82*	*0.71*	*0.79*	*0.79*	*−0.81*	*−0.87*	0.27
LSA			–	*0.94*	*0.96*	*0.94*	*0.97*	*0.98*	*0.99*	*0.99*	*0.71*	*0.70*	*0.79*	*−0.66*	*−0.67*	0.45
LAI				–	*0.87*	*0.93*	*0.94*	*0.96*	*0.97*	*0.98*	*0.84*	*0.82*	*0.86*	*−0.81*	*−0.81*	0.52
LN					–	*0.91*	*0.93*	*0.91*	*0.89*	*0.87*	*0.79*	*0.79*	*0.80*	*−0.86*	*−0.91*	0.41
CH						–	*0.95*	*0.96*	*0.95*	*0.92*	*0.72*	*0.76*	*0.83*	*−0.75*	*−0.80*	0.28
SH							–	*0.94*	*0.93*	*0.90*	*0.76*	*0.80*	*0.84*	*−0.74*	*−0.76*	0.36
LDW								–	*0.92*	*0.98*	*0.69*	*0.68*	*0.77*	*−0.64*	*−0.65*	0.45
RDW									–	*0.87*	*0.82*	*0.75*	*0.90*	*−0.73*	*−0.70*	0.32
SDW										–	*0.72*	*0.69*	*0.71*	*−0.65*	*−0.65*	0.66
SPAD											–	*0.96*	*0.93*	*−0.95*	*−0.90*	0.40
NDVI												–	*0.92*	*−0.98*	*−0.96*	0.34
GI													–	*−0.88*	*−0.85*	0.14
CWSI														–	*0.98*	−0.36
CT															–	−0.33
ST																–

Italic Pearson product-moment correlation coefficients are significant at $P \leq 0.05$ for the corresponding parameters

0.82 and 0.97. The leaf area index is another leaf parameter that represents the ratio of total leaf area to cropped soil surface. It is an important variable used as a reference tool to predict plant growth, evapotranspiration, and the photosynthetic primary production in vegetation among other uses (Parker 2020). At 80 DAS, this index was higher under normal irrigation, in particular in the presence of the water retainer. When irrigation was restricted, the same treatment showed the highest drop in LAI (−43%), which proves that the organic hydrogel performs better under normal irrigation as observed for aerial biomass as well (Table 4). In fact, both parameters are very highly correlated as presented in Table 5 ($r = 0.98$). The reduction in LAI under deficit irrigation could be rationally explained by the reduction in leaf size and number of leaves due to limited water availability in soil (Liu et al. 2012).

Plant growth parameters measured at 80 DAS showed also significant positive intercorrelations, testifying to their interconnected variation patterns and the strict relationship with soil water status (Kumar et al. 2017). Besides, this date corresponds to the regular farming practice of the first maize cut as a regenerating fodder crop that can be harvested up to nine times per year. In this study, plant growth parameters represented globally by canopy height and shoot weight for fodder crops were more significant under normal irrigation (Table 4). In addition, the synthetic water retainer was the most efficient in terms of aerial biomass yield when water supply was adequate (155, 88, and 53 g DW for N-WS, N-DS, and N-IS, respectively) (De Jesus Souza et al. 2016). Consequently, SH followed the same variation pattern as well (Table 4). This was generally correlated to the variation of water status in soil for the same group of treatments despite the very little difference observed for soil water tensions as shown in Fig. 5 (Yang et al. 2020). Water deficit significantly affected the agromorphological parameters of maize plants. As for the first group of treatments conducted under normal irrigation, the reductions in the agronomic traits was more pronounced for plants grown on unamended soils. The two soil amendments mitigated this growth inhibition with respect to control soil. For instance, LSA per plant were 1121, 1195, and 1476 cm^2 for D-IS, D-WS, and D-DS treatments, respectively. However, all measured parameters were significantly reduced when comparing the same soil treatments under normal and deficit irrigation (Table 4). For instance, average LSA per plant was reduced by 18%, 50.3%, and 12.9% for IS, WS, and DS treatments, respectively. Shoot dry weight followed the same decrease pattern: −17.7%, −55.6%, and −21.8%.

These events of reduced plant growth have been defined by Ahluwalia et al. (2021) as signs of insufficient water supply, a major abiotic stress that causes significant setbacks to agricultural productivity. The obtained results are in agreement with those observed by AbdAllah et al. (2021) for corn plants grown on soil amended with a polymer superabsorbent. The decrease in total biomass, leaf area, and shoot/root biomass ratio as well as their physiological changes can be associated with their drought hardening (Song et al. 2019). The structural adjustment in leaf area would imply an effective way to limit water loss, and the greater allocation to roots would inevitably improve water uptake, allowing a more favorable plant water balance and gas exchange capacity under drought (AbdAllah et al. 2021; Langner et al. 2021). Under deficit irrigation, organic waste compost application significantly improved most of plant parameters with respect to the commercial water absorbent and eventually the untreated soil (Table 4). In addition to higher SWC (Table 3), TN content in soil increased significantly (0.36%), highlighting the importance of organic waste materials in improving both the physical and chemical properties of amended soils (Hamdi et al. 2019). In this regard, the nutrients and microorganisms contained in compost allow for improving soil fertility by direct enrichment with macro- and microelements as well as by the activation of OM mineralization (Hamdi et al. 2007). The latter process would subsequently result in the beneficial slow release of mineralized nutrients into the soil such as nitrogen (Cassity-Duffey et al. 2020; Rodríguez-Espinosa et al. 2023a, b). However, the immediate objective of mitigating water deficiency to maintain crop production was attained in this study as treatments D-DS and D-WS showed comparable fodder maize yields (biomass) compared with unamended soil (Table 4).

Effect of soil treatments on maize physiological properties

Relative chlorophyll content (SPAD readings) was affected by water deficit stress for all treatments when compared with normal irrigation (Table 6). As such, decreases of 16%, 11.4%, and 20% were observed for treatments D-IS, D-WS, and D-DS, respectively. Accordingly, this decline was highly correlated to water status in soil by showing negative correlation with SWT presented in Table 5. In addition, the improvement of leaf properties such as the leaf area and water content was likely to be closely associated with chlorophyll content as well ($r = 0.71$). In fact, chlorophyll content and plant photosynthesis are strictly correlated because photosynthetic pigments allow plants to absorb energy from light (Hailemichael et al. 2016). Water stress can affect both associated parameters due to pigment degradation by hydrolytic enzymes (Zgallaï et al. 2005). In particular, Song et al. (2019) showed that severe and prolonged water stress during the seedling stage of maize plants damaged the structure of the photosynthetic membrane and resulted in lower chlorophyll content than plants that did not experience water stress at the seedling stage. While chlorophyll measurements were not significantly variable among treatments, numerically higher values were consistently observed in presence of the water-absorbing hydrogel in soil. In this regard, strong correlations were found with other plant parameters enhanced by the presence of the water retainer as well such as LAI ($r = 0.84$) and RDW ($r = 0.82$). Some studies have considered chlorophyll invariance under stress as a form of physiological resilience (Tongo et al. 2014). Indeed, for elms grown during drought with a polymer superabsorbent, the chlorophyll content was negatively correlated with the concentration of the soil conditioner (hydrogel) (Kargar et al. 2017). Others have even reported that hydrogel has little or no effect on plant performance (Tongo et al. 2014). In this study, chlorophyll content in leaves did not reflect the effect of soil amendments as was obvious with biomass yield, the most sought parameter for fodder crops.

The normalized difference vegetation index (NDVI) has primarily been established as a reliable tool for assessing the consequences of climate change on plant biodiversity, vegetation greenness and phenology, and primary productivity (Bushra et al. 2019). Neigh et al. (2008) indicated that green leaves have high visible light absorption together with high near-infrared reflectance, resulting in positive NDVI values. In contrast, water and bare soil have negative or close to zero values, respectively. As presented in Table 6, the NDVI decreased under deficit irrigation for all treatments but was consistently lower for unamended soils. The maximum amplitude of variation for NDVI was obtained for WS (13%) followed by IS (11%), while the lowest decrease was recorded for DS (7%). Therefore, the highest NDVI value under deficit irrigation was observed in presence of organic

Table 6 Effect of different soil treatments on physiological parameters of fodder maize plants at the end of the field study

Treatments	SPAD	NDVI	GI	CWSI	CT (°C)	ST (°C)
Normal irrigation						
N-IS	32 ± 1.6^{ab}	0.71 ± 0.02^{ab}	23.41 ± 0.36^{c}	0.11 ± 0.02^{cd}	26 ± 0.27^{d}	32 ± 0.64^{d}
N-DS	35 ± 1.6^{a}	0.75 ± 0.02^{a}	36.31 ± 0.36^{a}	0.04 ± 0.02^{e}	25 ± 0.27^{d}	43 ± 0.64^{a}
N-WS	34 ± 1.6^{a}	0.76 ± 0.02^{a}	33.82 ± 0.36^{b}	0.04 ± 0.02^{de}	25 ± 0.27^{d}	34 ± 0.64^{bc}
Deficit irrigation						
D-IS	27 ± 1.6^{c}	0.63 ± 0.02^{c}	1.47 ± 0.36^{f}	0.40 ± 0.02^{a}	31 ± 0.27^{a}	33 ± 0.64^{cd}
D-DS	31 ± 1.6^{abc}	0.70 ± 0.02^{ab}	5.60 ± 0.36^{d}	0.16 ± 0.02^{c}	27 ± 0.27^{c}	43 ± 0.64^{a}
D-WS	27 ± 1.6^{bc}	0.66 ± 0.02^{bc}	2.60 ± 0.36^{e}	0.28 ± 0.02^{b}	28 ± 0.27^{b}	35 ± 0.64^{b}

Values are means of triplicate ± standard errors (SE). Means in the same column followed by superscript letters in common are not significantly different at $P \leq 0.05$

SPAD chlorophyll content, *NDVI* normalized difference vegetation index, *GI* conductance index, *CWSI* crop water stress index, *CT* canopy temperature, *ST* soil surface temperature waste compost (0.70). The latter treatment led also to highest plant growth parameters as presented in Table 4. The variation of NDVI at the studied stage was similar to that found by Ghosh et al. (2003) who reported values ranging from 0.38–0.76 to 0.26–0.69 for fully and partially irrigated corn crops. Based on differences in reflectance due to pigment absorption and maximum reflectance caused by cellular structure, this index enables the quantification of green vegetation with the goal of estimating above-ground productivity (Lykhovyd 2020). It is closely related to a range of intercorrelated biomass variables such as LAI, green biomass, or green vegetation factor (Liu et al. 2012; Lykhovyd 2020). Accordingly, very high correlation coefficients were found with chlorophyll content ($r=0.96$) and LAI ($r=0.82$).

The application of a hydric stress to maize plants during 80 days generated a significant increase in CT for the three studied substrates, which was more pronounced in the case of unamended soil (+5 °C) (Table 6). Similarly, the analysis of variance of the mean values of the calculated GI and CWSI revealed a significant difference between normal and deficit irrigation for all soil treatments. In addition, all of the three plant parameters were highly correlated as presented in Table 5. The general tendency of increase in canopy temperature during water deficit was also observed in maize plants by De Jonge et al. (2015) in field experiment conducted during two successive summer seasons. They also noticed that the CT and leaf water potential were highly correlated in each major growth stage of maize plants. This trend suggests that canopy temperature and its subsequent thermal indices can be used to quantify water stress as well as irrigation schedule for cultivated plants (Fattahi et al. 2018). The surface soil temperature in presence of compost was significantly higher under both irrigation regimes than the rest of treatments due to variations in light reflection (Fig. 6). Deguchi et al. (2009) pointed out that compost application increases ST by decreasing evaporation from the soil surface as well. This was highlighted by lower ST values in absence of any soil amendments (Table 6). In addition, Simmons et al. (2013) noticed an increase of ST by 2–4 °C in soil amended with compost compared with soil alone and attributed that to the microbial activity associated with the exothermic decomposition of soil organic matter.

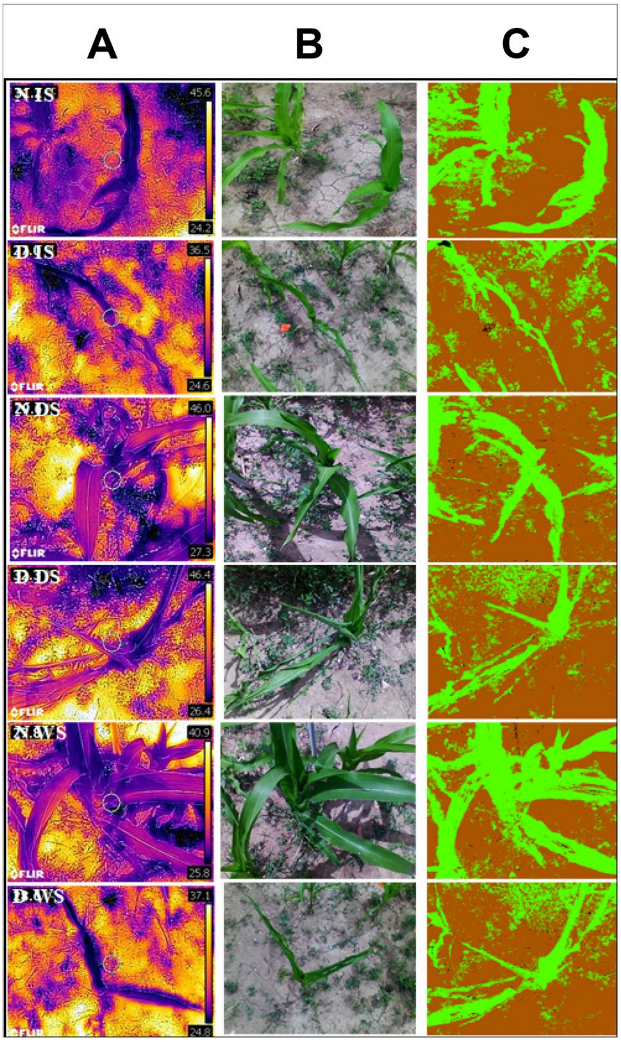

Fig. 6 Infrared thermal images for all treatments. *N* normal irrigation, *D* deficit irrigation. *IS* control (unamended) soil, *DS* soil amended with organic waste compost, *WS* soil treated with commercial water retainer. **A** Canopy and soil thermal image, **B** corresponding RGB image, **C** masked from both soil and shadowed leaves. Different colors in the image on the left (**A**) correspond to different temperatures

Conclusion

This study compared the performance of organic waste compost and synthetic water retainer in alleviating the consequences of soil water stress on fodder maize production. Compared to adequate water supply, the deficit irrigation affected plant growth in all treatments but mostly in unamended soil. Both amendments attenuated water stress effect by retaining more soil moisture. Even though both amendments ultimately led to comparable biomass yield after 80 days of cultivation, the sustainability of the production system appears to be more maintained in the presence of the organic compost. In fact, the agricultural reuse of compost is more economically and environmentally viable since it mitigates the risks of environmental pollution while improving soil physicochemical properties at reduced costs. In this regard, the compost produced locally from waste materials is more competitive than imported superabsorbents having shorter lasting effect (3 months only). Therefore, compost reuse could be favored as a sustainable and circular strategy for organic waste management in water-scarce agricultural systems.

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Data availability Data of soil/plant parameters are available upon request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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