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EFFECT OF AERATED IRRIGATION ON SOIL MICROENVIRONMENT AND COTTON GROWTH PROMOTION

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KEYWORDS

seedling emergence, soil water content, soil temperature, growth index, oxidoreductase, soil microorganisms.

ABSTRACT

Clay soil results in higher crop yield and quality than sandy soil. However, irrigation causes clay soil to slump easily, increasing compactness and decreasing soil oxygen content. This study investigated the effects of dry seeding and wet emergence on the soil microenvironment and cotton growth promotion in Xinjiang silt loam fields. The experimental design included three aerated and three non-aerated treatments. The results showed that aerated irrigation decreased dry density of the 0–20 cm soil layer to different degrees, the field capacity increased to different degrees, and the dry density and field capacity of the 20-30 cm soil layer did not change among the different treatments. The dry density and field capacity of WP2 treatment changed the most, the dry density of 0-10 cm and 10-20 cm soil layer were respectively 1.28 g cm^{-3} and 1.27 g cm^{-3}, and the field capacity were respectively 35.23% and 35.7%. Under the same irrigation quota, the soil water content of the aerated treatments was lower than that of the non-aerated treatments. Aerated irrigation inhibited the horizontal diffusion of water and facilitated downward water transport. The WP2 treatment had the highest peak soil temperature at depths of 10 and 20 cm, and the WP2 treatment had the highest numbers of bacteria, fungi, actinomycetes, urease, and catalase activities, seedling emergence, primary root length, plant height, and stem thickness.

INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is an economically important crop that plays a pivotal role in national economy (Xing et al., 2018). Cotton occupies a dominant position in China's cotton industry (Li, 2019; Zhou et al., 2020), accounting for 45–50% of the cropping area in Xinjiang, and the income from cotton planting accounts for 60–65% of the total income of cotton farmers (Zhang et al., 2020). However, Xinjiang is an arid region with water shortage, with an average precipitation of 154 mm per year, which is only 23.0% of the average for the whole of China; the main cotton-producing areas are irrigated agriculture in Xinjiang, and the irrigation water utilization coefficient is at a low level (Zhao et al., 2016). As the problem of water shortage in the region continues to intensify, there are not enough water resources to meet the requirements of cotton fields for winter and spring irrigation measures to ensure soil moisture when cotton is sown, which can seriously limit the development of the cotton farming industry. Therefore, the effective use of limited water resources to meet the needs of cotton is a bottleneck that must be overcome (Er et al., 2022). The selection of appropriate irrigation techniques and the targeted implementation of water conservation strategies can play an important role in improving crop production efficiency and the effective use of limited water resources (Su et al., 2011; Su et al.,

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2014;). Dry sowing and wet emergence is a planting technique that requires little winter and spring irrigation before sowing and ensures the normal emergence of crops via drip irrigation after sowing. The small amount of water needed has considerable advantages for water conservation (Han et al., 2022). Currently, dry sowing and wet emergence techniques have been successfully applied to cotton (Xiao & Yao, 2013), sunflower (Zhang et al., 2015), and maize (Yang et al., 2018). Previous studies have mainly examined the effects of irrigation systems on soil moisture content, soil salt transport, ground temperature, and seedling emergence status (Wang et al., 2012; Zhang et al., 2013). However, dry sowing and wet emergence technology have high requirements for soil texture and salinity content, yet research on these methods are currently distributed in agricultural fields with sandy or loamy soils of moderate to mild salinity; few studies have been conducted on clay loam or clay soils.

Soil texture is the basis of soil productivity and an important component of soil physical properties (Li et al., 2004). Differently textured soils vary considerably in physical and chemical properties, which can affect soil water, fertilizer, gas, heat, and salt migration and transformation. These processes in turn affect plant growth and development (Gao et al., 2014; Bacq-Labreuil et al., 2019). Clay soils have greater potential for high yield and quality crop cultivation than sandy soils because of their different characteristics. Water infiltration, evaporation, and salt transport frequency are all faster in sandy soils, meaning clay soils retain water better and hinder salt transport. Furthermore, under the same irrigation quota, chalky-sandy clay loam soils have higher water content (Abilovski et al., 2019; Zhou et al., 2019), along with stronger nutrient adsorption and fixation (Zhang et al., 2014; Zhao et al., 2020). However, clay soil is prone to post-irrigation slumping, warms more slowly than sandy soil, and has greater difficulty exchanging air with the atmosphere. These characteristics are detrimental to dry-seeding and wet-emergence planting techniques for cotton fields.

Aerated subsurface drip irrigation uses water to ventilate the crop root zone, solving the problems of soil consolidation and oxygen deficiency. This method ensures that the oxygen demands of both crop roots and soil microorganisms are met (Su, 2004). Aerated irrigation research often investigates effects on soil microenvironments. For example, subsurface aerated irrigation was found to decrease the number of soil macropores and increase the number of micropores, while also improving soil pore connectivity (Lei et al., 2017a; Yang et al., 2019). Other benefits include promoting heat exchange between soil and atmosphere, maintaining uniform soil temperature, and increasing soil oxygen saturation (Wang et al., 2016). As a result, aerated irrigation increases soil microbial abundance and enzyme activity (Ben-noah & Friedman, 2016), as well as water and fertilizer uptake rates (Li et al., 2016a). In turn, root vigor is enhanced (Niu et al., 2012a), contributing to the accumulation of root length and aboveground (leaves, stems, and dry fruit) biomass (Niu et al., 2012a). Aerated irrigation has been found to improve crop yield (potatoes: Chen et al., 2019) and quality (e.g., significant increase in vitamin C and soluble solid content in tomato: Essah & Holm, 2020).

Despite these findings, we still know little regarding how aerated irrigation causes systematic changes in soil physicochemical properties and structure (Li et al., 2016b). Few studies have been conducted on combining aerated irrigation with dry sowing and wet emergence techniques to promote cotton seedling growth in clay loam soils.

Therefore, in this study, we conducted experiments in light saline clay loam soil with different volumes of aerated and non-aerated irrigation water to determine effects on dry sowing and wet emergence of cotton. We buried underground drip irrigation tapes in narrow rows of cotton and used them to apply emergent water. We measured soil physical and chemical properties, soil temperature, seedling emergence rate, plant height, and stem thickness. Our overall goal was to solve the problems of sloughing and poor seedling emergence in clay loam soils when using dry sowing and wet emergence technology, thus improving their applicability. These findings should benefit efforts to improve cotton cultivation and alleviate water shortages in Xinjiang.

MATERIAL AND METHODS

Study site

The experiment was conducted in 2021, and the study site was located in Hailou Town (41.25°N, 82.70°E, 986 m above sea level) in Shaya County, Xinjiang, China. The climate is a typical warm temperate, extreme continental arid desert, with annual rainfall <100 mm, annual evaporation >2000 mm, and groundwater burial depth >3 m. The soil type is loamy (Table 1).

TABLE 1. Soil particle size.

Soil depth (cm)	>0.05 mm (%)	0.05–0.002 mm (%)	<0.002 mm (%)	Soil texture
0-10	35.7	55.2	9.1	Loamy soil
10-20	41.2	53.0	5.8	Loamy soil
20-30	39.9	51.3	8.8	Loamy soil
30-40	36.9	55.0	8.1	Loamy soil
40-60	39.1	52.3	8.6	Loamy soil
60-80	22.4	68.6	9.0	Loamy soil

Experimental design

This study used Cotton No. 11 for all experiments. Before plowing, 10 kg of diammonium phosphate and 5 kg and potassium sulfate were applied to each hectare. Next, the soil was harrowed and leveled with a tractor and a combined tiller, then compacted. A total of 2250 mL of 33% herbicide (pendimethalin) was sprayed per hectare. Drip irrigation tape in narrow rows of cotton was placed in the soil at a depth of 10 cm. The drip flow rate was 2.1 L h^{-1} and drip spacing was 20 cm.

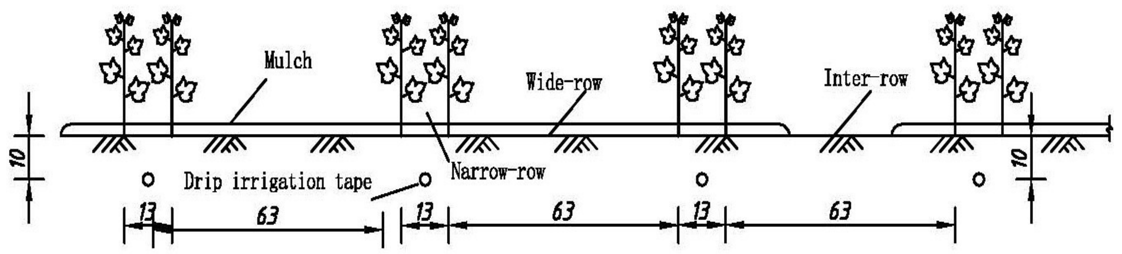


FIGURE 1. Schematic of planting patterns. Unit: cm

The cotton field was aerated with an aerator (super micron, Summer Spring Technology Company, China) connected to the main pipe. The aerator produced micro- and nanobubbles of 200 nm to 4 μm in size. Bubble content was between 84–90%, bubble average rise rate was 4–8 mm s^{-1}, and inlet volume was 2 L min^{-1}. A water meter was installed at the front end of the supermicron aerator inlet to measure non-aerated (pure) irrigation water. For drip irrigation, the valve was opened to ensure that irrigation pressure was consistently above 0.1 MPa. Other variables that were maintained at a constant level were irrigation water temperature (14°C) and irrigation water mineralization (1.8 g L^{-1}).

Irrigation occurred on April 16, 2021. The experiment was divided into two conditions, totaling six treatments (WP1–6) comprising different aerated volumes and different irrigation quotas (Table 2). For WP1–3, irrigation quotas were 150 m^3 ha^{-1}, 225 m^3 ha^{-1}, and 300 m^3 ha^{-1}, respectively, coupled with aerated volumes of 3600 L ha^{-1}, 5400 L ha^{-1}, and 7200 L ha^{-1}. For WP4, WP5, and WP6, irrigation quotas were 150 m^3 ha^{-1}, 225 m^3 ha^{-1}, and 300 m^3 ha^{-1}, respectively, without aeration. Subsurface drip irrigation was used, and each treatment was repeated three times in an experimental plot area of 80 m^2.

TABLE 2. Experimental design.

Treatments	WP1	WP2	WP3	WP4	WP5	WP6
Irrigation quotas (m^3 ha^{-1})	150	225	300	150	225	300
Aerated volumes (L ha^{-1})	3600	5400	7200	0	0	0

Indicator measurements

Soil temperature

Soil temperature at the surface water level (depth 0–5 cm) was measured using the Doctor of Soil (JXBS-3001-SCY-PT2, Qiaoqi, China) at 10:00 from the first day after irrigation to cotton emergence. After irrigation for seedling emergence, vertical-depth ground temperature was measured every 30 min using an automatic temperature and humidity recorder (EasyLog-USB-2, LASCAR, UK), buried 10 and 20 cm deep.

Soil water content

Surface soil water content was measured at 10:00 using a Doctor of Soil (JXBS-3001-SCY-PT2, Qiaoqi, China) on the first day post-irrigation until cotton emergence. Soil from wide and narrow rows per treatment was sampled in 10 cm intervals using a soil auger at depths of 0–40 cm. Mass moisture content was determined using the drying method and then multiplied by dry soil capacity to obtain volumetric moisture content.

Soil dry density and field capacity

After seedling emergence, soil dry density and field capacity were determined with the cutting ring method from in situ soil samples and the drying method. The cutting ring method sampled from a depth of 30 cm and a layer every 10 cm (Liu et al., 2021).

Soil microbial population

Three 50 g mixtures from the 0–20 cm soil layer were randomly sampled per treatment, placed in self-sealing bags, and frozen in a -20°C refrigerator. Colony counts were calculated after culturing bacteria in beef paste peptone agar medium, fungi in Martin-Bengal Red agar medium, and actinomycetes in modified Gaucho 1 agar medium (Microbiology Laboratory, Nanjing Institute of Soil Science, 1985). Microbial colony counts were calculated as follows:

$$\text{Colony number} = M \times D \div m \quad (1)$$

where:

M is average number of colonies, CFU;

D is dilution multiple, time, and

m is mass of dried soil, g.

Soil enzyme activity

To determine microbial content, a 5 g soil sample was combined with 1 mL of toluene in a 50 mL volumetric flask and shaken gently with a stopper for 15 min. Then, 5 mL of 10% urea solution and 10 mL of citrate buffer (pH 6.7) were added to the flask and mixed carefully. The sample was then incubated at 37°C for 24 h, diluted with 38℃ distilled water until toluene floated above the scale, shaken, and filtered. The filtrate (1 mL) was added to a 50 mL volumetric flask, diluted to 10 mL with distilled water, shaken with 4 mL of sodium phenol solution and 3 mL of sodium hypochlorite solution, then rested for 20 min. Subsequently, the mixture was diluted to the scale and absorbance at 578 nm was measured. To determine urease activity, absorbance of the control sample was subtracted from absorbance of the test sample. The concentration of ammoniacal nitrogen was derived from the standard curve.

Air-dried soil (2 g) was placed in a 100 mL triangular flask and filled with 40 mL of distilled water and 5 mL of 0.3% hydrogen peroxide solution. A control flask was also established, filled with 40 mL of distilled water and 5 ml of 0.3% hydrogen peroxide solution without adding soil. Flasks were placed in a shaker for 20 min. Subsequently, 5 mL of 3N sulfuric acid was added to stabilize undecomposed hydrogen peroxide. The suspension was filtered through slow-speed filter paper. The filtrate (25 mL) was aspirated and titrated with 0.1 N potassium permanganate to a light pink endpoint.

Seedling emergence rate

The number of seedlings and empty holes were counted.

Plant height, stem thickness, and root length

Before the field was sprayed with shrunburl amine, 10 groups of seedlings were randomly selected from each treatment. Plant height and stem thickness were measured using a straightedge and electronic Vernier caliper (accuracy 0.01 mm), then averaged per treatment. Three cotton seedlings per treatment were randomly uncovered to a depth of 10 cm for measuring the main root length with a straightedge.

Statistical analysis

Data were quantified in Excel 2019, plotted in Origin 2018, and analyzed in SPSS version 19.0. Differences between groups were determined with ANOVA, followed by multiple comparisons.

RESULTS AND DISCUSSION

Effect of aerated irrigation on dry density and field capacity in the tillage layer

Soil dry density and field capacity of the 0–30 cm soil layer are shown in Table 3. Aerated irrigation decreased dry density in the 0–10 cm and 10–20 cm soil layers more than non-aerated irrigation. At 30 cm depth, however, dry densities did not differ ($P > 0.05$) between the WP1–WP6 conditions. In non-aerated treatments, dry densities of the 0–10 cm and 10–20 cm soil layers increased with increasing irrigation quota. Thus, under the same amount of irrigation water, aerated irrigation decreased dry capacity only in the 0–10 cm and 10–20 cm soil layers compared with the non-aerated treatment. The interaction between aerated volume and irrigation quota significantly influenced dry density ($P < 0.05$). The WP2 condition resulted in the largest drop in dry density, meaning that the magnitude of the decrease did not vary linearly with the amount of aerated water.

In non-aerated treatments, field capacity decreased with increasing irrigation quota. In aerated treatments, aerated volume, irrigation quota, and their interaction all influenced field capacity, which did not change linearly with aerated volume or irrigation quota. For the same amount of irrigation water, aerated treatments decreased field capacity in the 0–10 cm and 10–20 cm soil layers compared with non-aerated treatments. The WP1 treatment had 1.02 and 1.03 times higher field capacity than the WP4 treatment in the two soil layers, respectively, whereas WP2 field capacity was 1.14 and 1.13 times higher than WP5 field capacity. Additionally, WP3 had 1.12 and 1.09 times higher field capacity than WP6 in the two soil layers, respectively. Field capacity was highest in WP2, owing to the interaction between aerated volume and irrigation quota ($P < 0.01$).

TABLE 3. Dry density and field capacity at different depths in irrigation treatments.

Experiments	Indicators	Dry density (g cm^{-3})			Field capacity (%)		
	Soil depth (cm)	0-10	10-20	20-30	0-10	10-20	20-30
Aerated treatments	WP1	1.37±0.07cd	1.4±0.05c	1.61±0.05a	32.26±0.16c	33.29±0.35b	30.43±0.52a
	WP2	1.28±0.08d	1.27±0.07d	1.54±0.06a	35.23±0.57a	35.7±0.17a	31.17±0.28a
	WP3	1.32±0.07cd	1.44±0.08bc	1.54±0.04a	33.62±0.29b	33.23±0.37b	30.52±0.68a
Non-aerated treatments	WP4	1.41±0.05bc	1.46±0.05bc	1.59±0.05a	31.54±0.27cd	32.29±0.19c	30.59±0.32a
	WP5	1.51±0.04ab	1.53±0.07ab	1.59±0.04a	30.8±1.01de	31.48±0.41d	31.04±0.94a
	WP6	1.58±0.04a	1.62±0.07a	1.62±0.06a	30.13±0.52e	30.54±0.60e	30.08±0.84a
F	Aerated volume	37.12**	27.27**	2.04	123.40**	217.91**	0.2
	Irrigation quota	1.76	6.07	0.62	8.41**	30.41**	2.51
	Aerated volume×Irrigation quota	5.64*	3.32*	1.33	18.45**	27.11**	0.32

Note: Data are mean ± standard deviation (n = 3), and different letters in the same column indicate significant differences at $P < 0.05$. *$P < 0.05$, **$P < 0.01$.

Effect of aerated irrigation on soil water content at different locations

Effect of aerated irrigation on soil water content at horizontal locations

The results of the soil water content at the horizontal locations in the different treatments are shown in Table 4. The interaction between aeration and irrigation quota did not affect soil water content ($P > 0.05$). The soil water content of the aerated and non-aerated treatments increased with the irrigation quota. The water content of different locations of the WP1–WP6 treatments was 0 cm > 5 cm > 10 cm, and the soil water content decreased away from the drip irrigation zone. Affected by aeration, the difference in soil water content at 0, 5, and 10 cm in the aerated treatments was higher than in the non-aerated treatments. This indicated that aeration promoted soil water infiltration and inhibited horizontal water transport.

Under the same irrigation quota, the soil pore space of aerated treatments was occupied by air, and the soil water content of aerated treatments was lower than that of non-aerated treatments; the soil water content of the WP1 treatment was 2.2 %, 2.5 %, and 2.8% lower than that of the WP4 treatment at 0, 5, and 10 cm, respectively, and the soil water content of the WP2 treatment was 1.9%, 1.6%, and 2.0% lower than that of the WP5 treatment at 0, 5, and 10 cm, respectively; and the WP3 treatments had 0.5, 0.7, and 1.0% lower soil water content than the WP6 treatment at 0, 5, and 10 cm, respectively. The difference in the soil water content between the aerated and non-aerated treatments at different locations decreased with increasing irrigation water content. This also indicates that the air content in the soil did not increase with an increase in the aerated volume if the irrigation quota and aerated volume increased simultaneously.

TABLE 4. Water content of surface soil at different locations in irrigation treatments.

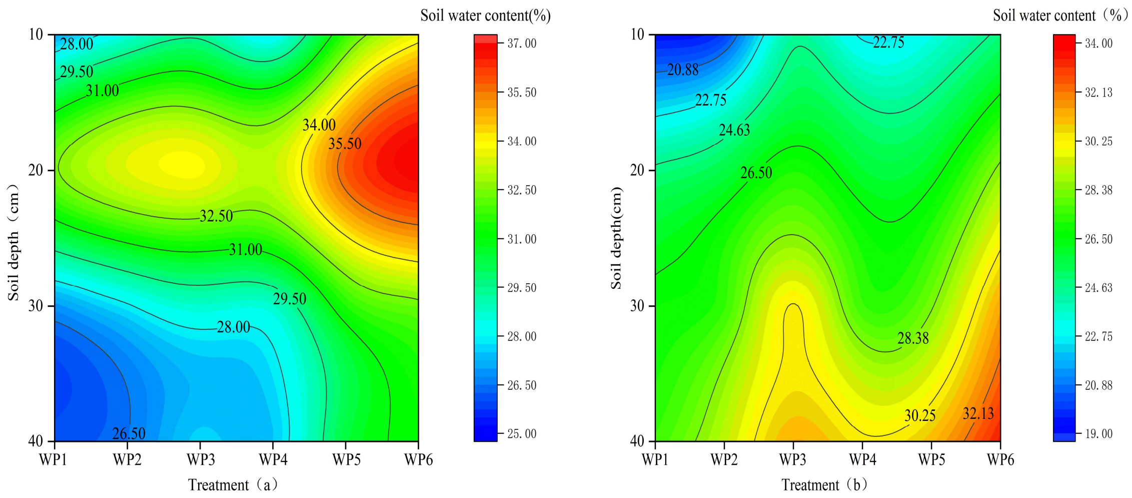
Experiments	Horizontal locations (cm)	0	5	10
Aerated treatments	WP1	27.1±0.53d	23±0.70d	20.6±1.32d
	WP2	28.2±0.46cd	24.3±0.36c	21.9±0.30c
	WP3	31.7±1.05a	27.7±0.30a	25.2±0.53a
Non-aerated treatments	WP4	29.3±0.46bc	25.5±0.46b	23.4±0.50b
	WP5	30.1±0.53b	25.9±0.43b	23.9±0.30b
	WP6	32.2±0.53a	28.4±0.30a	26.2±0.53a
F	Aerated volume	26.79**	57.60**	36.83**
	Irrigation quota	57.73**	119.33**	48.92**
	Aerated volume×Irrigation quota	3.13	6.08	2.67

Note: Data are mean ± standard deviation (n = 3), and different letters in the same column indicate significant differences at $P < 0.05$. *$P < 0.05$, **$P < 0.01$.

Effect of aerated irrigation on soil water content at different vertical depths

The soil water contents at different vertical depths for the different treatments are shown in Fig. 2. The soil water content at different locations was closely related to the aerated volume and irrigation quota. The soil water content in the different treatments was WP6 > WP5 > WP3 > WP2 > WP4 > WP1. As the soil layer deepened, the soil water content in each treatment increased and then decreased. The soil water content in the 10–20 cm soil layer was higher than that in the other soil layers. In the two soil layers of 20-30 cm and 30-40 cm, the soil water content of the aerated treatments was higher than that of the non-aerated treatments under the same irrigation quota, indicating that aerated irrigation was beneficial for the downward movement of soil water. However, the soil water content in the 0-20 cm soil layer did not reach field capacity before the downward movement of water occurred.

The rate of downward movement of water in the aerated treatments was faster than that in the non-aerated treatments, the rate of vertical transport slowed down, and the water transported to the wide-row soil was lower than that in the non-aerated treatments. Therefore, for the same irrigation quota, the soil water content of the aerated treatments was lower than that of the non-aerated treatments: WP1 < WP4, WP2 < WP5, and WP3 < WP6.



(a) (b)

FIGURE 2. Changes in water content at different soil depths of aerated (a) and non-aerated irrigation (b) treatments.

Effect of aerated irrigation on vertical and horizontal soil temperature

Effect of aerated irrigation on surface soil temperature

Surface soil temperature at seedling emergence (Table 5) were influenced by surface soil water content across different treatments in the following order: 0 cm < 5 cm < 10 cm for WP1–WP6. Soil temperature increased as measurements took place farther away from the drip irrigation belt. In WP1, soil temperature at 0 cm was 1.3°C and 1.8°C lower than at 5 cm and 10 cm, respectively. Overall, surface soil temperature at 0, 5, and 10 cm in aerated treatments decreased gradually as irrigation quota increased.

For the same irrigation quota, aerated treatments yielded higher soil temperature than non-aerated treatments. The WP1 treatment increased soil temperature at 0, 5, and 10 cm compared to the WP4 treatment, but the difference was not significant (P > 0.05). In contrast, the WP2 treatment significantly increased (P < 0.05) soil temperatures at 0, 5, and 10 cm by 1.5°C, 1.5°C, and 1.7°C, respectively, compared with the WP5 treatment. The WP3 and WP6 treatments also differed in soil temperatures across the various distances from the irrigation belt. The WP2 treatment had the best warming effect of all treatments.

TABLE 5. Ground temperature at different horizontal locations in irrigation treatments.

Experiment	Horizontal locations (cm)	0	5	10
Aerated treatments	WP1	17.3±0.50b	18.6±0.20b	19.1±0.43ab
	WP2	18.3±0.26a	19.2±0.30a	19.8±0.56a
	WP3	17.1±0.20b	17.6±0.20cd	18.3±0.46bc
Non-aerated treatments	WP4	17.1±0.40b	18.1±0.36bc	18.5±0.36bc
	WP5	16.8±0.36bc	17.7±0.20cd	18.1±0.46cd
	WP6	16.4±0.26c	17.2±0.40d	17.4±0.40d
F	Aerated volume	24.00**	34.56**	25.39**
	Irrigation quota	8.04**	24.18**	10.59**
	Aerated volume×Irrigation quota	5.38*	6.66*	2.41

Note: Data are mean ± standard deviation (n = 3), and different letters in the same column indicate significant differences at P < 0.05. *P < 0.05, **P < 0.01.

Effect of aerated irrigation on soil temperatures at different depths

The effect of irrigation treatments on daily variations in soil temperature at different depths are shown in Fig. 3. Daily minimum soil temperatures at 10 cm for WP1–WP6 treatments all occurred at 9:00, being 15.28°C, 15.00°C, 15.17°C, 16.25°C, 15.92°C, and 16.17°C, respectively. Aerated treatments had lower minimum soil temperature than non-aerated treatments for the same irrigation quota: WP1 was 0.97°C lower than WP4, WP2 was 0.92°C lower than WP5, and WP3 was 1.00°C lower than WP6. Thus, aerated treatments had weaker soil heat storage capacity than non-aerated treatments. The highest soil temperatures for aerated treatments (WP1–WP3) were 31.58°C, 33.17°C, and 31.75°C, respectively, all occurring at 17:00. The highest soil temperatures for non-aerated treatments (WP4–WP6) occurred at 1 h later at 18:00, being 30.83°C, 30.25°C, and 29.25°C. Thus, soil temperatures in aerated treatments were 1.02, 1.10, and

1.09 times higher than temperatures in non-aerated treatments under the same irrigation quota. Daily average ground temperatures of WP1–WP6 were 22.71, 22.74, 22.49, 22.53, 22.08 & 21.91°C, respectively, indicating considerable variation in maximum intra-day temperatures of aerated treatments, which had a strong effect on the daily average ground temperature.

Data for 20 cm depth in the WP3 treatment are missing because of a geothermometer malfunction. Daily soil temperatures in WP1–WP6 treatments reached the lowest point around 11:00, being 17.67℃, 17.27℃, 17.42℃, 18.00℃, and 17.58℃, respectively; non-aerated treatments had higher minimum soil temperature than aerated treatments. Peak daily changes in soil temperature for WP1–WP6 were 27.42℃, 27.00℃, 26.50℃, 26.25℃, and 25.75℃, respectively, while average daily soil temperatures were 22.07℃, 21.99℃, 21.53℃, 21.77℃, and 21.36℃. Thus, aerated treatments resulted in higher peak and average daily soil temperature than non-aerated treatments.

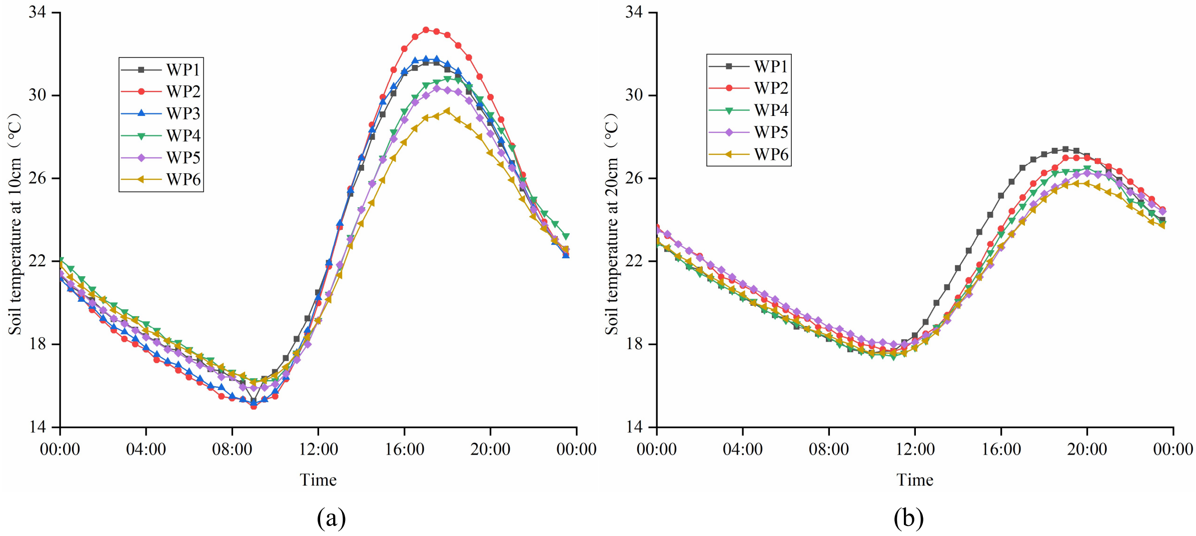


FIGURE 3. Characteristics of daily variation in ground temperature at 10 cm (a) and 20 cm (b) across different irrigation treatments.

Effect of aerated irrigation on soil microorganisms and soil enzyme activity

Effect of aerated irrigation on abundance of soil bacteria, fungi, and Actinomycetes

Microbial abundance is shown in Table 6. Aerated volume and irrigation quota separately influenced the abundance of soil bacteria, fungi, and Actinomycetes, as did their interaction. Fungal and Actinomycetes abundance did not differ between the WP6 treatment and the other non-aerated treatments. Soil bacterial, fungal, and Actinomycetes abundance in aerated treatments were higher than abundance in non-aerated treatments because of the aerated volume × irrigation quota effect. However, abundance did not increase when aerated volume and irrigation quota increased. Notably, the number of Actinomycetes did not differ between WP1 and WP4, indicating that aerated water levels were not an influential factor.

Soil bacteria abundance in aerated wide rows was higher than in non-aerated rows. Aerated volume, irrigation quota, and their interaction had significant effects on the soil fungal population (P < 0.01), with aerated volume in particular promoting fungal growth. Aerated treatments resulted in more soil fungi than non-aerated treatments, with WP2 having the highest fungal abundance. Aerated volume, irrigation quota, and their interaction all influenced Actinomycetes populations, but they did not differ significantly between the WP1–WP4 treatments. Soil bacteria, fungi, and Actinomycetes abundance were higher in the narrow rows than in the wide rows. This outcome was likely because irrigation volume and aerated volume had less effect on the wider rows than on the narrow rows.

TABLE 6. Number of soil microorganisms at different locations in irrigation treatments.

Project	Locations	Narrow rows			Wide rows		
	Indicators	Bacteria ×10^7 (cfu/g)	Fungi ×10^2 (cfu/g)	Actinomycetes ×10^4 (cfu/g)	Bacteria ×10^7 (cfu/g)	Fungi ×10^2 (cfu/g)	Actinomycetes ×10^4 (cfu/g)
Aerated treatments	WP1	5.49±0.08b	20.19±1.24b	4.73±0.33a	5.32±0.26a	13.48±1.20b	3.68±0.34a
	WP2	6.37±0.77a	27.3±1.44a	4.93±1.05a	5.35±0.35a	17.37±0.75a	3.99±0.38a
	WP3	5.21±0.32bc	9.01±0.77c	3.95±0.33ab	5.30±1.04a	12.8±0.96b	4.06±0.65a
Non-aerated treatments	WP4	4.66±0.34cd	6.16±0.47d	4.02±0.10ab	4.53±0.20ab	4.72±0.33c	3.63±0.81a
	WP5	4.41±0.09d	4.23±0.14e	3.25±0.13b	4.06±0.04ab	3.34±0.37d	2.39±0.74b
	WP6	4.22±0.08d	2.74±0.27e	1.67±0.98c	3.16±1.62b	2.56±0.31d	0.52±0.02c
F	Aerated volume	51.84**	1246.14**	28.50**	13.66**	998.35**	42.88**
	Irrigation quota	4.87*	209.13**	10.89**	1.17	19.67**	9.18**
	Aerated volume×Irrigation quota	4.07*	140.41**	2.44*	1.06	20.29**	14.57**

Note: Data are mean ± standard deviation (n = 3), and different letters in the same column indicate significant differences at $P < 0.05$. *$P < 0.05$, **$P < 0.01$.

Effect of aerated irrigation on soil enzyme activity

Table 7 shows soil urease and catalase activities in the irrigation treatments. Aerated volume, irrigation quota, and their interaction all influenced soil urease activity in the narrow rows of irrigation treatments. In non-aerated conditions, soil urease activity decreased with increasing irrigation quota. However, in aerated conditions, soil urease activity was affected by the aerated volume × irrigation quota effect and did not increase as either aerated volume or irrigation quota increased. Soil urease activity was highest in WP2 and was affected by the interaction between aerated volume and irrigation quota, as well as by the two variables individually, increasing by 15.6 mg 100 g^{-1} from WP5 levels at the same irrigation quota. Peroxidase activity was highest in WP2 and significantly different from levels in other treatments ($P < 0.05$). Soil catalase activity was higher in aerated treatments than in non-aerated treatments because of the interaction between aerated volume and irrigation quota.

Soil peroxidase activity in non-aerated treatments decreased as irrigation quota increased. However, in aerated treatments, peroxidase activity did not increase with increasing aerated volume or irrigation quota. Overall, soil peroxidase activity was higher in aerated treatments than in non-aerated treatments. Aerated volume and irrigation quota both had significant main effects on soil urease activity in wide rows, but their interaction had no effect. Soil urease activity was highest in the WP2 treatment, but not significantly higher from activity in WP1, WP3, and WP4 treatments. Non-aerated treatments resulted in lower peroxidase activity than aerated treatments. Additionally, in non-aerated treatments, peroxidase activity decreased with increasing irrigation quota, but was only affected by aerated volume and not irrigation quota or the interaction term. Soil urease and catalase activities were higher in narrow rows than in wide rows because of aeration and the interaction effect.

TABLE 7. Soil urease and peroxidase activities at different locations in irrigation treatments.

Project	Locations	Narrow rows		Wide rows	
	Indicators	Urease activity (mg/100 g)	Catalase activity (mg/100 g)	Urease activity (mg/100 g)	Catalase activity (mg/100 g)
Aerated treatments	WP1	244.09±1.33b	1.30±0.01b	239.52±2.67a	1.30±0.04a
	WP2	249.43±2.85a	1.34±0.03a	239.64±1.95a	1.29±0.02a
	WP3	239.48±2.16c	1.30±0.02b	238.52±3.93a	1.29±0.04ab
Non-aerated treatments	WP4	236.92±1.27c	1.28±0.01b	236.67±1.85ab	1.27±0.01abc
	WP5	233.83±0.29d	1.24±0.01c	233.08±1.88bc	1.24±0.03bc
	WP6	232.32±0.57d	1.24±0.01c	231.21±0.67c	1.22±0.01c
F	Aerated volume	161.75**	55.88**	139.95**	16.28**
	Irrigation quota	19.96**	3.71	15.68*	1.81
	Aerated volume×Irrigation quota	12.83**	6.90**	8.56	0.70

Note: Data are mean ± standard deviation (n = 3), and different letters in the same column indicate significant differences at $P < 0.05$. *$P < 0.05$, **$P < 0.01$.

Effect of aerated irrigation on seedling emergence and growth indexes

Seedling emergence rates and growth indices are shown in Table 8. Aerated treatments yielded higher seedling emergence rates and growth indices than non-aerated treatments, indicating that aerated irrigation provides more oxygen to cotton seeds and induces deeper root establishment.

The WP2 treatment resulted in the highest seedling emergence, main root length, plant height, and stem thickness, respectively 1.10, 1.18, 1.01, and 1.06 times higher than values in the WP1 treatment, as well as 1.09, 1.02, 0.97, and 1.05 times higher than values in the WP3 treatment.

TABLE 8. Seedling emergence rate and growth index of different irrigation treatments.

Project	WP1	WP2	WP3	WP4	WP5	WP6
Seedling emergence rate (%)	81.3±0.06c	89.8±0.1a	82.5±0.21b	80±0.29c	75.8±0.15d	69.2±0.15e
Main root length (cm)	4.5±0.12bc	5.3±0.12a	5.2±0.12a	4.3±0.12b	3.6±0.10d	3.8±0.12cd
Plant height (cm)	6.8±0.06c	6.9±0.17ab	7.1±0.12a	6.6±0.17bc	5.6±0.17d	5.7±0.15d
Stem thickness (mm)	2.34±0.08bc	2.47±0.03a	2.36±0.02a	2.24±0.02b	2.06±0.01c	2.22±0.02b

Note: Data are mean ± standard deviation (n = 10, 3), and different letters in the same row indicate significant differences at $P < 0.05$.

Soil microbes are not the main driving force for recycling soil organic matter and nutrients into humus. Microbes directly affect soil oxidation, nitrification, ammonification, and nitrogen fixation, promoting organic matter decomposition and the transformation of soil substances. Their ability to induce the movement and exchange of materials and energy vertically make microorganisms essential to the soil ecosystem (Zou et al., 2005). However, tillage systems, mechanical milling, irrigation systems, and other anthropogenic influences cause excessive soil densification (Tang et al., 2011). These processes restrict air exchange between the soil and atmosphere, leading to root hypoxia (Niu et al., 2012b) and inhibition of aerobic respiration in soil microorganisms. In turn, beneficial microbial activity is limited, along with the seed germination that is dependent on it, including the germination of major crops like cotton (Li et al., 2015). Oxygen delivery to crop roots can increase soil microbial activity, improve the inter-root growth environment, and promote plant growth (Lei et al., 2017b). In this study, we found that irrigation quotas were a major influence on soil microbes; bacterial, fungal, and Actinomycetes abundance in narrow rows decreased with increasing irrigation quotas (Table 5). This effect was mainly related to soil pores being occupied by water, squeezing air out of the soil (Fig. 2). This decrease in soil oxygen content caused a corresponding drop in aerobic microorganisms. Aerated irrigation can promote the microbial population via increasing or connecting soil pores and lowering dry density (Yang et al., 2019), delivering air to soil in the tillage layer and raising soil oxygen content (Yu et al., 2022). In our study, the decrease in dry soil density caused an increase in the percentage of soil pore volume and soil field capacity (Table 2). However, soil water content did not increase in actual aerated irrigation because of a decrease in dry soil density and an increase in field capacity. This phenomenon can be explained by the fact that although aerated irrigation increases the percentage of soil pore volume, the pores are not all occupied by irrigation water. Instead, air dilutes the concentration of irrigation water in the soil, providing sufficient oxygen for cotton seed emergence and for soil microorganisms, thus increasing enzymatic activity (Table 5). In addition, aeration connects soil pores, increasing the capacity of downward water transport, while limiting horizontal water transport.

Under equal weather and agronomic practices, soil temperature in agricultural fields is influenced by several factors, including soil texture, moisture content, and compactness. Sandy loam soils increases soil temperature more easily than clay loam soils, mainly due to the specific heat capacities of different soil textures. Cotton requires a higher soil temperature during the seedling emergence period, and a slow increase in soil temperature prolongs its emergence. A large amount of irrigation water causes a rapid drop in soil temperature, especially when the source of irrigation water is snow and ice meltwater. Furthermore, the high water content of soil after irrigation increases the risk of seed rot and non-emergence. Although aerated irrigation cannot change soil texture, it can change soil water content and compactness to influence soil temperature (Lv et al., 2022). Moreover, aerated irrigation increases the soil pore ratio (Lei et al., 2017a; Yang et al., 2019), decreases soil dry density and specific heat capacity, and improves soil permeability. These characteristics allow soil temperature to rapidly increase when exposed to surface heat radiation. In our study, we observed that aerated soil had lower water content under the same irrigation quota non-aerated soil, mitigating the magnitude of soil cooling by irrigation water. However, because aerated soil had lower specific heat capacity and water content than non-aerated soil, the peak soil temperature was higher under aerated irrigation than under non-aerated irrigation during the day and lower at night (Fig. 3).

Within a certain range, cotton yield increases with planting density (Xiao et al., 2021). At a fixed planting density, seedling emergence is one of the main factors determining cotton yield. The dry seeding and wet emergence technologies used in our study are subject to the drip irrigation effect (Rzicka et al., 2007) and to the dual effects of dripping and easy slumping in slit loam soils. All of these are detrimental to cotton emergence. Consistent with our findings (Table 4), previous research has shown that subsurface aerated irrigation can induce deep root establishment and development (Xu, 2020), promote rapid root nutrient uptake, and enhance the growth of aboveground plant parts (Wang et al., 2018). However, under water-air intercropping conditions, high levels of emerging water and aerated volume are not the most favorable for cotton emergence and growth. Cotton emergence rate is influenced by soil water, fertilizer, air, heat, and salt (Cao et al., 2020). From the results of our experiments, we considered that the irrigation quota and aerated volume in the WP2 treatment were optimal for cotton.

CONCLUSIONS

Aerated irrigation can significantly decrease soil dry density and improve field capacity in cotton fields. Among the treatments, the WP2 treatment resulted in the highest reduction in soil dry density and the highest increase in field capacity. At the same irrigation quota, aerated irrigation reduced soil water content, promoted the downward movement of water, and inhibited the horizontal transport of water; thus, water was retained in the 10–20 cm soil layer. Horizontal soil temperatures of both aerated and non-aerated treatments was in the order of $0 < 5 < 10$ cm, and aerated treatments had higher soil temperature than non-aerated treatments. Under the same irrigation quota, soil temperatures at 10 cm and 20 cm peaked in a shorter period of time for aerated treatments than for non-aerated treatments Peak and diurnal temperature difference was also higher for aerated treatments than for non-aerated treatments. The number of microorganisms (bacteria, fungi, and Actinomycetes) and soil enzymatic activity (urease and catalase) were higher in the aerated treatment than in the non-aerated treatments; narrow rows were higher than wide rows, and the number of microorganisms and enzyme activities were the highest in the WP2 treatment. Aerated treatments resulted in higher emergence and growth indices than non-aerated treatments, with WP2 found to be optimal.

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