Ridge-Furrow Planting System and Wheat Straw Mulching Effects on Dryland Sunflower Yield, Soil Temperature, and Moisture

Majid Gholamhoseini,* Aria Dolatabadian, and Farhad Habibzadeh

ABSTRACT

The current study uses 2-yr trial data set to investigate the impacts of ridge-furrow planting system and wheat (*Triticum aestivum* L.) straw mulching on sunflower (*Helianthus annuus* L.) yield and some soil parameters. Field experiments were conducted in 2014 and 2015 in two different locations (Tehran and Mashhad Provinces, Iran). The experiments were laid out in a randomized complete block design comprised of four treatments, including control that is, neither ridge-furrow planting system nor wheat straw mulching (RF_0M_0); ridge-furrow planting system without wheat straw mulching (RF_1M_0); ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface (RF_1M_{50}); and ridge-furrow planting system with full covering (100%) of the soil surface with wheat straw mulch (RF_1M_{100}). The RF_1M_0 treatment could not increase sunflower yield, but the application of 50 and 100% wheat straw mulch significantly increased seed yield by10 and 18%, respectively. For both years and sites, on average the maximum seed yield was found with the RF_1M_{100} treatment (1629 kg ha^{-1}), while the minimum value (1318 kg ha^{-1}) was related to RF_0M_0 treatment. Wheat straw mulching reduced soil temperature and increased soil water storage, organic C and microbial biomass C. We concluded that the ridge-furrow planting system with full coverage of the soil surface with wheat straw mulch could be critical in the cultivation of sunflower under arid and semiarid areas, where water is the most important factor in determining plant growth and yield.

Core Ideas

- Ridge-furrow system promoted sunflower seed yield, applying straw mulch further increased yield.
- Improved sunflower yield was explained by optimized water supply and thermal balance.
- Wheat straw mulch could reduce risk of heat stress.
- Application of wheat straw mulching improved soil biological properties.
- The RF_1M_{100} effectively increased soil water storage and biomass accumulation.

Published in Agron. J. 111:3383–3392 (2019)
doi:10.2134/agronj2019.02.0097
Supplemental material available online

Sunflower is one of the world's most important oilseed crops. According to FAO's estimates, in 2016, Iran's sunflower-harvested area was 41,119 ha accounting for 39,855 t sunflower seed. The average sunflower yield in Iran is around 1114 kg ha^{-1}, 32.19% lower than the world's average (1643 kg ha^{-1}). Drought is the main factor that negatively affects sunflower yield, especially in arid and semiarid regions. In the light of global climate change, especially drought occurrence, it is essential to optimize genetic × environment × management (G×E×M) interaction to maximize crops yield under such conditions. We can overcome climate change negative impacts through several management strategies, for example, increasing irrigation (Léllis et al., 2017) and fertilizers efficiency (Liu et al., 2017), taking advantages of zero or minimum tillage (Liu et al., 2010), ridge-furrow cultivation (Hösl and Strauss, 2016), and finally applying natural or artificial mulches (Busari et al., 2015).

Ridge-furrow cultivation can be practiced through either seed sowing on the ridges, which is mostly practiced in cooler regions, or seed sowing in the furrows to capture more rainfall, which is usually practiced in arid or semiarid regions (Eldoma et al., 2016). In a study, Zhang et al. (2015) found that ridge-furrow planting system could increase water use efficiency and seed yield by 1.8 and 1.9 times, respectively, when compared to flat tillage. Several studies have also revealed that ridge-furrow planting system increases crop yield in arid and semiarid areas mainly through improving soil moisture storage, prolonging the period of crop water availability, and enhancing crop growth (Gu et al., 2017; Zhang et al., 2015).

One of the effective water-saving methods is to reduce evaporation from the soil surface and increase rainwater detention by applying straw mulch (Daryanto et al., 2017; Chakraborty et al., 2010). Straw mulch has been increasingly used as surface mulch in crop production in regions where crop stubbles are not used as fuel or fodder (Huang et al., 2006). In wheat

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Abbreviations: HI, harvest index; MBC, microbial biomass carbon; RF_0M_0, neither ridge-furrow planting system nor wheat straw mulching; RF_1M_0, ridge-furrow planting system without wheat straw mulching; RF_1M_{50}, ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface; RF_1M_{100}, ridge-furrow planting system with full covering (100%) of the soil surface with wheat straw mulch; SMQ, soil microbial quotient; SOC, soil organic carbon; SWC, soil water content; SWS, soil water storage.

production, straw can be chopped and spread evenly on the soil surface. Straw mulch helps to retard the loss of moisture from the soil and reduce the soil temperature. It also alters the soil microclimate and expected to reduce evaporation and increase dry matter production during the growth period (Gu et al., 2017). The positive effects of straw mulch have been reported in several studies. For example, Rusinamhodzi et al. (2011) found that mean maize yield was ~1 t ha^{-1} higher when long-term no-tillage, crop rotation and straw mulch were practiced. Recently, Pittelkow et al. (2014) reported that crops yield increased by 7.3% when no-tillage and straw mulch were implemented.

Although there are several studies focusing on the importance of the ridge-furrow planting system, there are only a few studies investigating the effects of ridge-furrow planting system and wheat straw mulch on sunflower phenology, yield, and soil parameters in drought-prone regions. Therefore, in the current study, we examined sunflower growth, yield, and yield components as well as some soil parameters in four planting systems, that is, flat tillage, ridge-furrow planting system, ridge-furrow planting system along with partial wheat straw mulch (covering 50% of the soil surface) and ridge-furrow planting system along with full wheat straw mulch (covering 100% of the soil surface).

MATERIALS AND METHODS

Experimental Sites

The field trials were performed at two different sites in Tehran (35°41′ N, 51°19′ E,1215 masl), and Mashhad (36°18′ N, 59°36′ E, 995 masl), Iran, in 2014 and 2015 growing seasons. The rainfall and air temperature data on a daily basis are shown in the supplemental material (Supplemental Fig. S1). Prior to seed sowing, 20 soil samples were collected at the depth of 0 to 30 and 30 to 60 cm, air-dried, crushed, and evaluated for physical and chemical properties (Supplemental Table S1).

Experimental Design and Treatments

The seedbed was prepared by removing previous year's crop residue, wheat in 2014 and canola (*Brassica napus* L.) in 2015 using shallow plowing to 20-cm depth and removing the existing root networks and finally a disk in May. Trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)aniline] (3.5 L ha^{-1}) was used to control weeds as a pre-emergence herbicide, and then sunflower seeds were sown. The experimental plots were 10 m long and consisted of nine sowing rows spaced 0.7 m apart. Two-meter gaps between the blocks and 1 m distance between each plot were considered. Irrigation flow was controlled using polyethylene pipeline and a volumetric water meter.

The experiment was conducted using a randomized complete block design with four replications. At sowing time, four treatments including control, that is, neither ridge-furrow planting system nor wheat straw mulching (RF_0M_0); ridge-furrow planting system without wheat straw mulching (RF_1M_0); ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface (RF_1M_{50}); and ridge-furrow planting system with full coverage (100%) of the soil surface with wheat straw mulch (RF_1M_{100}) were randomized to each plot in each replication. Blizar cultivar, an early-maturing cultivar, was sown manually at the depth of 5 cm on 2 June in 2014 and on 5 June in 2015. The seeds were sown at higher sowing rate first, and then the plots were thinned at two-leaf stage (to 26 cm spacing) to achieve 55,000 plants ha^{-1}. Air-dried wheat straw were cut into 5 to 15 cm in length and manually applied between the ridges and furrows in both growing seasons on seedling establishment at the rate of 11 and 22 t ha^{-1} for 50 and 100% coverage treatments, respectively. These rates were calculated by applying wheat straw much on 1 m^2 of soil to reach half and full soil covering.

The irrigation was performed immediately after seed sowing using an installed pipeline and dropping-tube system. Irrigation scheduling was determined as previously described by Gholamhoseini et al. (2013). In both years and sites, irrigation was performed equally in all plots after depleting 70% of available water (approximately every 15–20 d) at the depth of root development. To monitor soil water content, time-domain reflectometry (TDR) tube access (TRIME-FM, Ettlingen, Germany) were inserted at the depth of 0 to 100 cm (at 0.2-m intervals). The soil was fertilized with urea (130 kg ha^{-1} in Tehran and 135 kg ha^{-1} in Mashhad) at seed sowing and flowering stages (the latter is the R2 stage described by Schneiter and Miller, 1981) and S fertilizer (60 kg ha^{-1} from gypsum). No K or P fertilizers were applied as recommended by a soil test (Supplemental Table S1).

Data Collection

Phenology

The BBCH-scale was used to identify the phenological development stages. Phenological development stages were recorded as the times at which 50% of plants reached the stage. We distinguished seedlings emergence (09: cotyledons emerge through soil surface), four fully expanding leaves (14: leaves [second pair] unfolded), beginning of flowering (61: ray florets extended, disc florets visible in outer third of inflorescence) and physiological maturity (87: back of the anthocarp yellow, bracts marbled brown. Seeds about 75–80% dry matter). Sunflower growing degree days (GDD) were calculated by subtracting the sunflower's base temperature of 6.5°C from the average daily air temperature. The average daily air temperature was calculated by averaging the daily maximum and minimum air temperatures.

Soil Temperature

Soil temperature at the depth of 5 cm was measured using digital thermometers probes (Model TCAV, Campbell Scientific, Inc., Logan, UT). The data were collected at the V4, R2, R5, and R8 growth stages (Schneiter and Miller, 1981) at 0600, 1200, and 1800 h. Ten observations were taken; each from different points of the same treatment. The mean daily temperature was calculated using three daily readings.

Soil Water Content and Soil Water Storage

Soil water content (SWC) (%) was measured in 20-cm increments at the 0- to 100-cm soil depth in both years and sites using TDR data at the V4, R2, R5, and R8 sunflower growth stages. Soil water storage (SWS) (mm) was calculated using Eq. [1].

$$\mathrm{SWS\ (mm)} = \mathrm{SWC\ (\%)} \times \mathrm{SD\ (mm)} \times \rho b\ (\mathrm{g\ cm^{-3}}) \quad [1]$$

where SD refers to the depth of soil layer (200 mm), and *p*b is soil bulk density, determined for whole soil profile (0–100-cm depth) and averaged at 1.46 cm^{-3} in Tehran and 1.44 cm^{-3} in Mashhad.

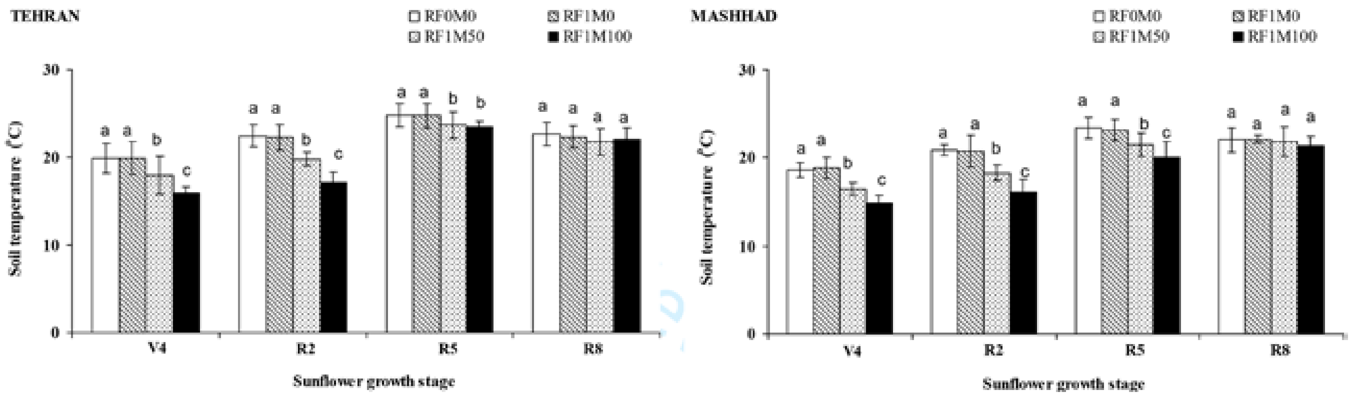

Fig. 1. Effect of treatments on soil temperature at different sunflower growth stages in (left) Tehran and (right) Mashhad. Means within each growth stage of each site followed by the same letter are not significantly different ($p \leq 0.05$). Bars show standard error.

Soil Organic Carbon, Soil Microbial Biomass Carbon, and Soil Microbial Quotient

After harvesting soil samples were collected from four locations in each plot using a hand auger at the depth of 15 cm and then sieved through 2-mm mesh sieve, then stored in airtight and moisture-tight plastic bags and kept at 4°C. Potassium dichromate oxidation and heating method were used to measure soil organic carbon (SOC) (Lu, 2000). Soil microbial biomass carbon (MBC) was determined through chloroform fumigation and K_2SO_4 extraction method (conversion coefficient *K* is 0.45) (Vance et al., 1987). The soil microbial quotient (SMQ) was calculated from the ratio of soil microbial biomass C to soil organic C.

Yield and Yield Components

Total aboveground dry matter and final seed yields were determined by harvesting the crop in a sampling area of 15 m^2 of each plot. Seed number per capitule was determined in 20 randomly selected plants. Seed weight was measured by randomly selecting 1000 seeds. The final sunflower seed yield was calculated as the product of yield components; that is, capitule density, seed number per capitule, and seed weight in each plot and standardized to a 14% water content. Harvest index (HI) was calculated by dividing the seed yield by aboveground dry matter.

Data Analysis

Analysis of variance was used to examine treatment effects on sunflower phenology, dry matter production, yield, and yield components as well as soil parameters using the General Linear Model Univariate in SAS. The Least Significant Difference (LSD) test was used to detect a significant difference between the treatments.

RESULTS

Soil Temperature and Sunflower Phenology

The effect of different treatments on soil temperature was more pronounced during the early stages of sunflower growth (V4 and R2 growth stages) rather than later growth stages (R5 and R8 growth stages) (Fig. 1). In addition, soil temperature was not significantly affected by ridge-furrow planting system. In other words, there was no significant difference during the whole growing season between RF_0M_0 and RF_1M_0 treatments (Fig. 1). Compared with RF_0M_0, RF_1M_{100} treatment significantly decreased soil temperature by 4 and 3°C at the V4 growth stage in Tehran and Mashhad, respectively. At the R2 growth stage, topsoil temperature was lower (4°C in Tehran and 3.5°C in Mashhad) under mulch treatments compared with the bare soil surface. Moreover, at the R5 growth stage (reproduction phase), RF_1M_{100} treatment could decrease topsoil temperature by 1.31°C in Tehran and 3.38°C in Mashhad, respectively. At the maturity stage (R8 growth stage), although the lower soil temperature was found in the RF_1M_{100} and RF_1M_{50} in both sites, no significant difference was detected between the treatments (Fig. 1). On the other hand, the lowest values of soil temperature were observed in RF_1M_{100} treatment in both sites and growing seasons, and also the extent of temperature reduction was greater at the R2 growth stage.

The total growth period of sunflower was not significantly affected by ridge-furrow planting system, but it was shortened by adding wheat straw mulch to the ridges as an average overall mulch treatment in two sites and years (Supplemental Table S2). In other words, GDD to reach physiological maturity was decreased as a result of increasing wheat straw mulch from 50 to 100%.

Soil Water Content and Soil Water Storage

At the V4 growth stage, the RF_0M_0 treatment caused the lowest SWC; in both sites, whereas the RF_1M_{50} and RF_1M_{100} treatments led to significantly higher SWC at the 0- to100-cm soil depth compared with other treatments (Fig. 2). The ridge-furrow farming system accompanied by wheat straw mulching increased SWC so that the increase in mulch quantity was parallel with the increase in SWC (Fig. 2). On average, SWC in RF_1M_{100} treatment was 32 and 29% higher than that in control and RF_1M_0 treatments, respectively. At the R2 growth stage, the maximum SWC at 0 to 80 cm soil profiles was found in RF_1M_{100} treatment, whereas the minimum SWC was obtained in RF_0M_0 and RF_1M_0 in Tehran and Mashhad, respectively (Fig. 3). The average of SWC at 0 to 80 cm soil profile was recorded as 17.9% in Tehran and 16.6% in Mashhad in RF_1M_{100} treatment, while it was found to be 17.3% in Tehran and 14.3% in Mashhad in RF_1M_{50}, 14.7% in Tehran and 11.8% in Mashhad in RF_1M_0, and 13.7% in Tehran and 13.1% in Mashhad in RF_0M_0. Soil moisture in RF_1M_0 treatment was almost equal to RF_0M_0 treatment; furthermore, soil moisture in these treatments was lower than the mulched treatments, whether in Tehran or Mashhad.

The RF_1M_{100} treatment caused the highest SWC at the R5 growth stage in both sites, especially in Mashhad at 0- to 80-cm soil depth (Fig. 4). On average, the difference between RF_1M_{100} and RF_1M_0 treatments in terms of SWC was 2.35% at 0- to 80-cm soil depth, which was directly related to the presence of wheat straw mulch. The soil layers deeper than 80 cm, showed constant

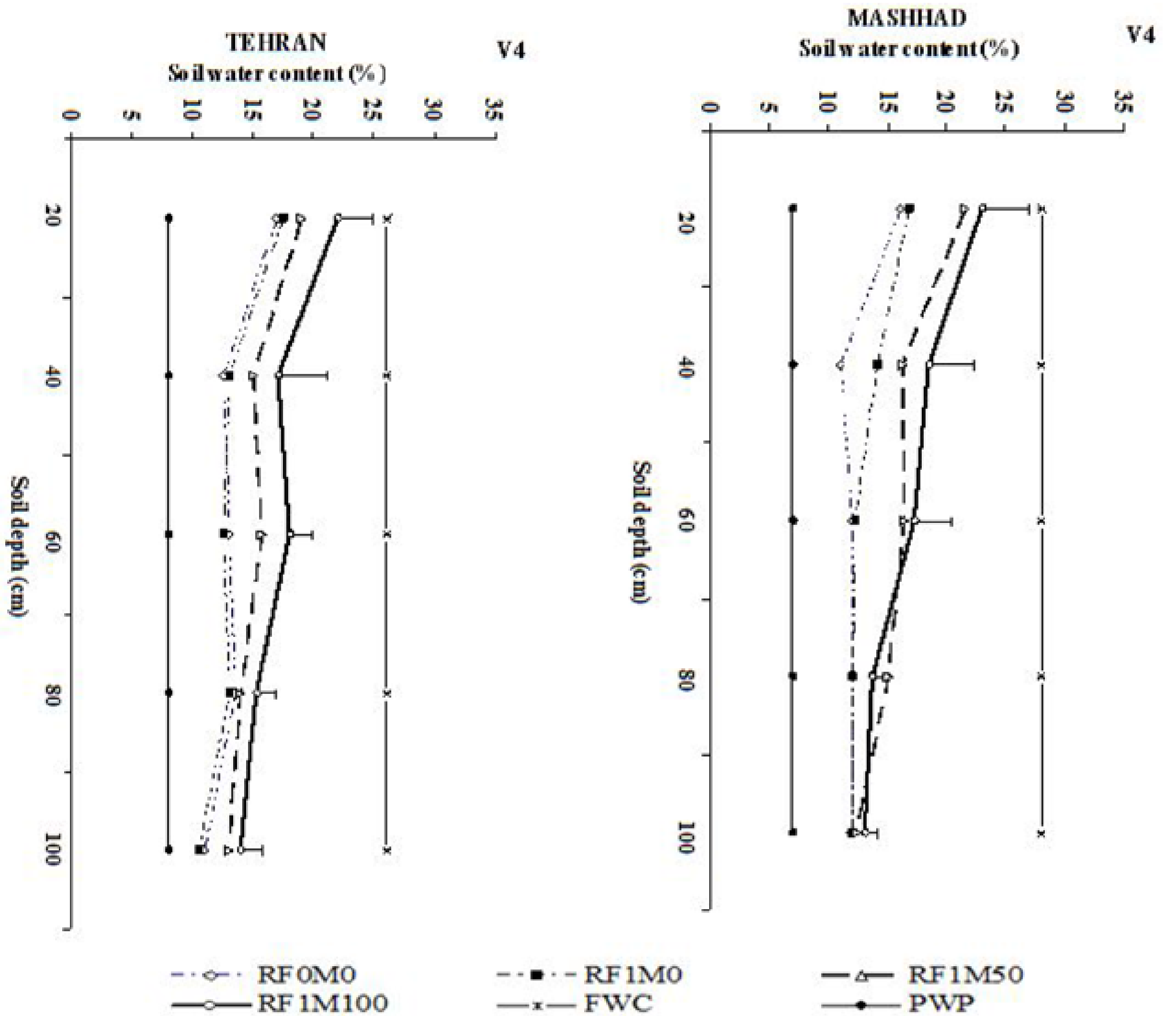

Fig. 2. Soil water content affected by different treatments at V4 sunflower growth stage in (left) Tehran and (right) Mashhad. RF_0M_0, neither ridge-furrow planting system nor wheat straw mulching; RF_1M_0, ridge-furrow planting system without wheat straw mulching; RF_1M_{50}, ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface; RF_1M_{100}, ridge-furrow planting system with full coverage (100%) of the soil surface with wheat straw mulch. PWP and FWC stand for the permanent wilting point and field water capacity, respectively. Bars stand for LSD at 0.05 levels.

soil moisture, indicating the quantity of irrigation water is not effective to recharge the soil water at such depths (Fig. 4). At the R8 growth stage, SWC at 0 to 100 cm soil layers, under mulching treatments was higher than that in mulch free treatments (Fig. 5). Among the treatments, RF_1M_{100} caused the maximum SWC in both sites. In Tehran, SWC in RF_1M_{100} was 20, 22, and 9% higher than that in RF_0M_0, RF_1M_0, and RF_1M_{50}, respectively. Also, in Mashhad, SWC in RF_1M_{100} was 18, 27, and 10% higher than that in RF_0M_0, RF_1M_0, and RF_1M_{50}, respectively.

At the V4 and R2 growth stages, RF_1M_{100} treatment showed the maximum SWS in both sites; however, there was no significant difference between RF_1M_{100} and RF_1M_{50} in Mashhad at V4 or in Tehran at R2 growth stage (Fig. 6). In both sites, SWS was higher in mulch-applied treatments (RF_1M_{100} and RF_1M_{50}) compared with mulch-free treatments (RF_1M_0 or RF_0M_0). In comparison to RF_0M_0 treatment, the average SWS (0–100 cm soil profile) significantly increased due to RF_1M_{100} and RF_1M_{50} treatments (61 and 41 mm at V4 and 46 and 31 mm at R2, respectively). At the R5 growth stage, SWS in mulch-applied treatments increased by 18 mm (in Tehran) and 26 mm (in Mashhad) compared with mulch-free treatments. At the maturity stage (R8), the maximum SWS was found in RF_1M_{100} treatment (237 and 222 mm in Tehran and Mashhad, respectively), whereas the minimum SWS was obtained in RF_0M_0 (196 mm) and RF_1M_0 (173 mm) treatments in Tehran and Mashhad, respectively (Fig. 6).

Soil Microbial Biomass Carbon, Soil Organic Carbon and Soil Microbial Quotient

Soil MBC, SOC, and SMQ were not significantly affected by ridge-furrow planting system across the sites and years, but increased by adding wheat straw mulch onto ridge-furrows (Table 1). The RF_1M_{100} treatment resulted in a significantly higher soil MBC, SOC, and SMQ compared with RF_1M_{50} treatment (Table 1). The results were the same across the sites and years (Table 1).

Dry Matter Yield, Yield Components, Seed Yield, and Harvest Index

The dry matter yield was ranked as follows: RF_1M_{100} > RF_1M_0 > RF_1M_{50} > RF_0M_0. In comparison to RF_0M_0, the

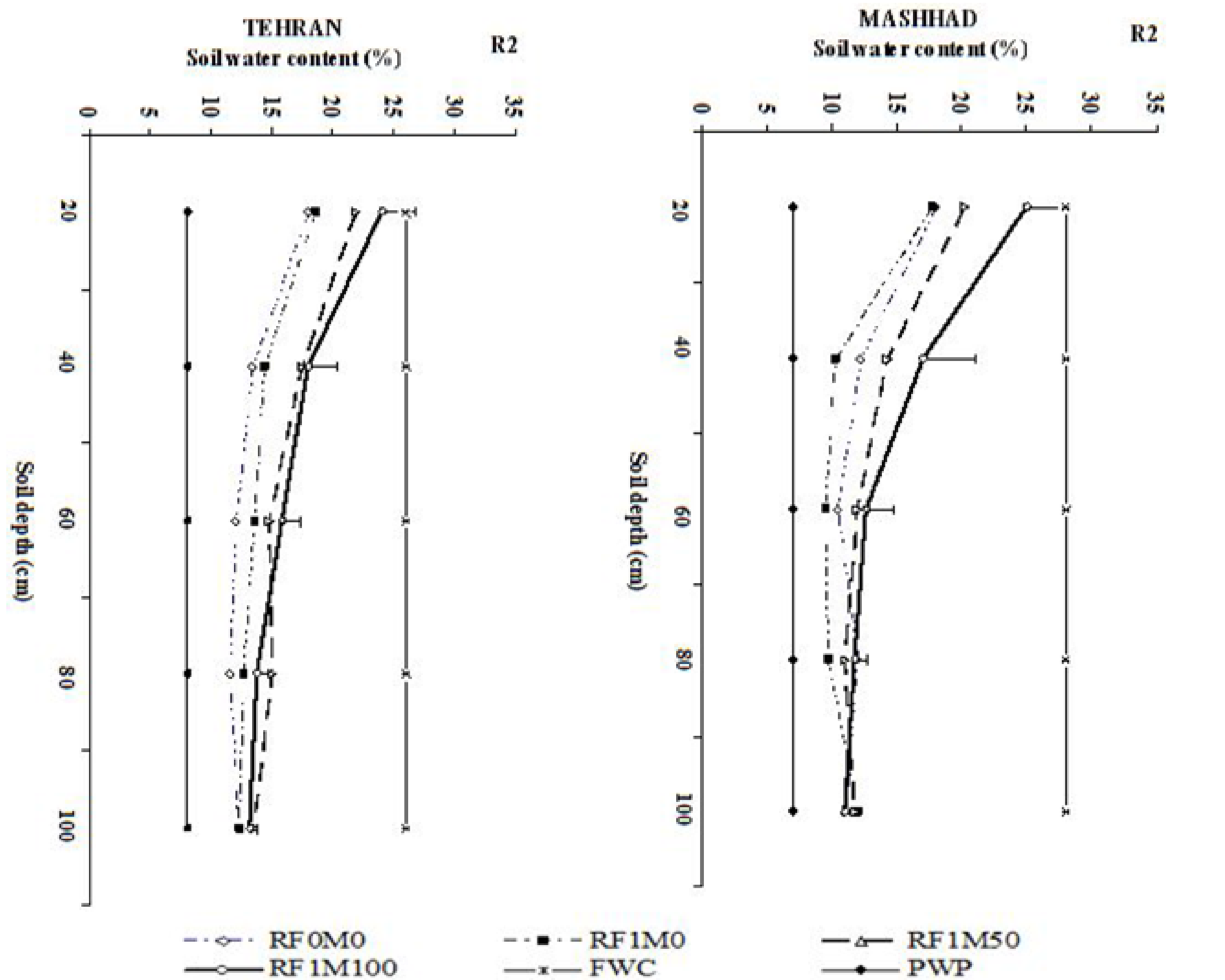

Fig. 3. Soil water content affected by different treatments at R2 sunflower growth stage in (left) Tehran and (right) Mashhad. RF_0M_0, neither ridge-furrow planting system nor wheat straw mulching; RF_1M_0, ridge-furrow planting system without wheat straw mulching; RF_1M_{50}, ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface; RF_1M_{100}, ridge-furrow planting system with full coverage (100%) of the soil surface with wheat straw mulch. PWP and FWC stand for the permanent wilting point and field water capacity, respectively. Bars stand for LSD at 0.05 levels.

average dry matter yield in RF_1M_{100}, RF_1M_0, and RF_1M_{50} treatments significantly increased by 462, 196, and 66 kg ha^{-1}, respectively (Table 2). In both years and experimental sites, RF_1M_{50} and RF_1M_{100} treatments resulted in significantly higher seed number per capitule and 1000-seed weight compared with RF_0M_0 and RF_1M_0 treatments (Table 2). However, there were no significant differences between the RF_0M_0 and RF_1M_0 treatments in terms of these parameters (Table 2). On the other hand, yield components were not significantly affected by ridge-furrow planting system. On average, seed number per capitule increased by 6, 14, and 15% in RF_1M_{100} treatment compared with RF_1M_{50}, RF_1M_0, and RF_0M_0, treatments, respectively. The 1000-seed weight in RF_1M_{100} treatment was also increased significantly, by 13, 29, and 31 g compared with RF_1M_{50}, RF_1M_0, and RF_0M_0 treatments, respectively. In comparison to RF_0M_0 treatment, seed yields in RF_1M_{100}, RF_1M_{50}, and RF_1M_0 treatments increased by 25, 16, and 7% in Tehran, and 22, 13, and 4% in Mashhad, respectively (Table 2). The increase in sunflower seed yield by ridge-furrow planting system and wheat straw mulch treatments was in part attributable to an increase in either seed number or the allocation of assimilates to the seeds, thus the HI was increased under using the ridge-furrow planting system, and a further increase was observed by applying RF_1M_{50} and RF_1M_{100} treatments. In both years and sites, the highest HI was obtained from RF_1M_{100} treatment (Table 2).

DISCUSSION

Soil temperature plays a significant role in plant growth and development; nonetheless, the effect of temperature is often implicitly presumed to be correlated with air, but not soil temperature. Recently, it has been reported that soil temperature more closely associates with crop development than air temperature (Sabri et al., 2018; González et al., 2009), so that plant growth is visibly affected by changes in soil temperature (Gan et al., 2013; Pramanik et al., 2015). From the results, we found that the effect of wheat straw mulch on soil temperature was more pronounced during the early stages of growth (V4 and R2 growth stages), because of the sparse crop cover compared to later growth stages (Fig. 1). In addition, we concluded that the application of wheat straw mulch could considerably reduce soil temperature during the sunflower growing period (Fig. 1). Reduction in soil temperature due to straw mulch application

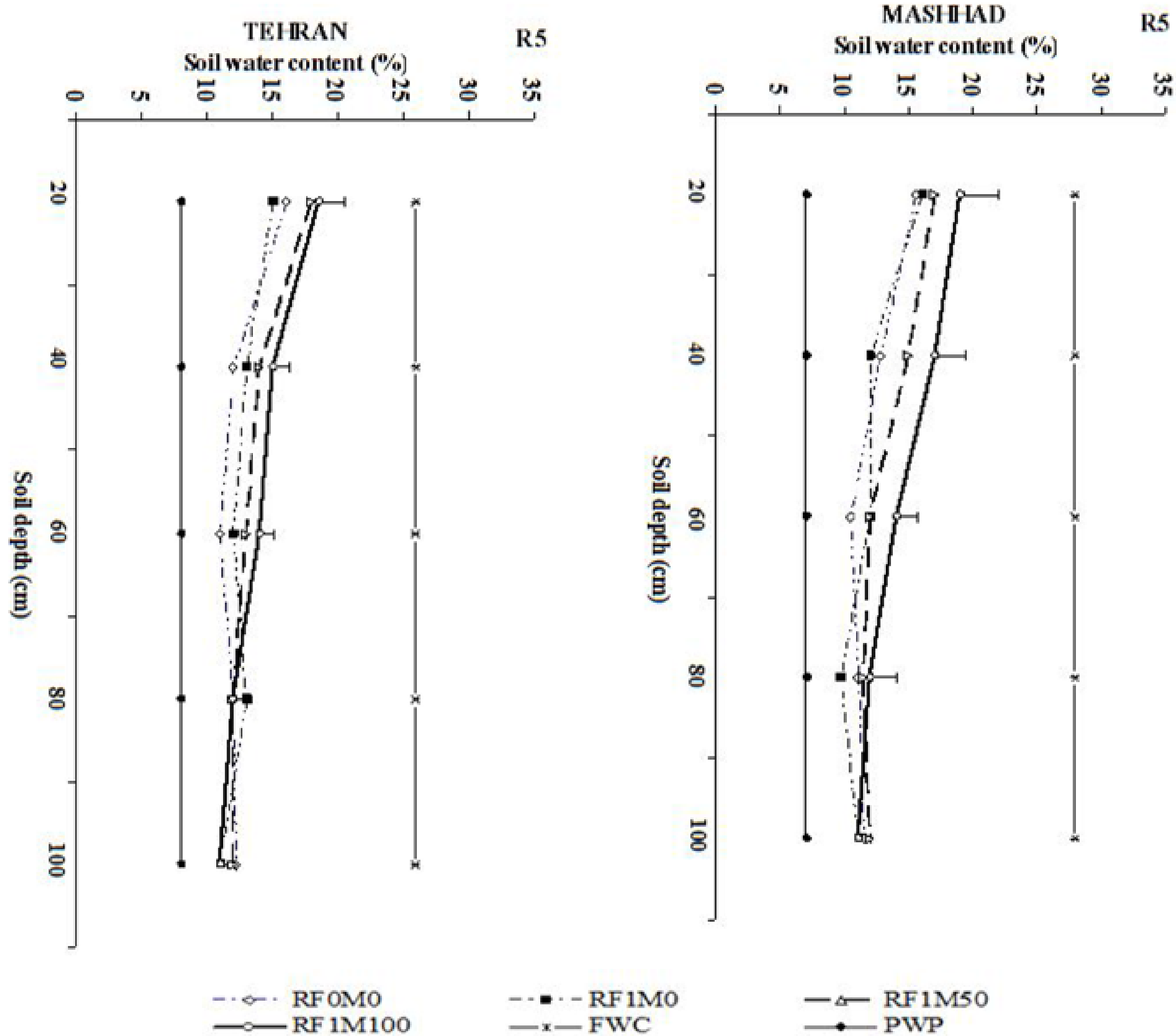

Fig. 4. Soil water content affected by different treatments at R5 sunflower growth stage in (left) Tehran and (right) Mashhad. RF_0M_0, neither ridge-furrow planting system nor wheat straw mulching; RF_1M_0, ridge-furrow planting system without wheat straw mulching; RF_1M_{50}, ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface; RF_1M_{100}, ridge-furrow planting system with full coverage (100%) of the soil surface with wheat straw mulch. PWP and FWC stand for the permanent wilting point and field water capacity, respectively. Bars stand for LSD at 0.05 levels.

can be described with two basic mechanisms, first the straw mulch reduces soil radiation absorption during the day and second, the straw mulch layer contains a significant amount of pore space (Chen et al., 2019). The majority of this pore space is likely to be filled with air, and the air is known to be an excellent insulator. The airspace in the mulched layer prevents energy conduction. Therefore, wheat straw mulch application caused lower soil temperature compared with control treatment. In the current study, RF_0M_0 and RF_1M_0 treatments showed the highest soil temperature and resulted in premature senescence in relation to RF_1M_{50} and RF_1M_{100} treatments. The results confirm that the wheat straw mulch would reduce the heat stress risk in the semiarid region, where the main advantage of mulch is to reduce soil temperature and then accelerate the early build-up of the canopy, especially in a hot summer. During the daytime, wheat straw mulch reduces soil radiation absorption, and at night, mulch reduces the outgoing heat radiation from the soil (Chen et al., 2019). Previous studies have reported that the soil thermal regime under straw mulching was different from that in bare soil, with soil temperatures often being lower under mulched surfaces than in non-mulched soils (Bristow, 1988; Sarkar et al., 2007). The major advantage of the ridge-furrow mulching system is that it promotes seedling establishment and improves plant growth. Several experiments have been conducted to examine the response of different crops to ridge-furrow mulching, and majority of them reported a positive response (Bu et al., 2013; Gan et al., 2013). Seedlings grown under mulches of crop straw emerge earlier and grow faster (Li et al., 2001) which is consistent with our findings of shorter growth period as a result of straw mulch. This suggests that the dry matter accumulation rate was improved substantially by applying mulch (Gu et al., 2017). Also, soil temperature depression due to straw mulch application was the major factor involved in enhancing dry matter production and shortening growth period.

In addition, mulch is known to conserve soil moisture. Sunflower grows during the summer period when temperature

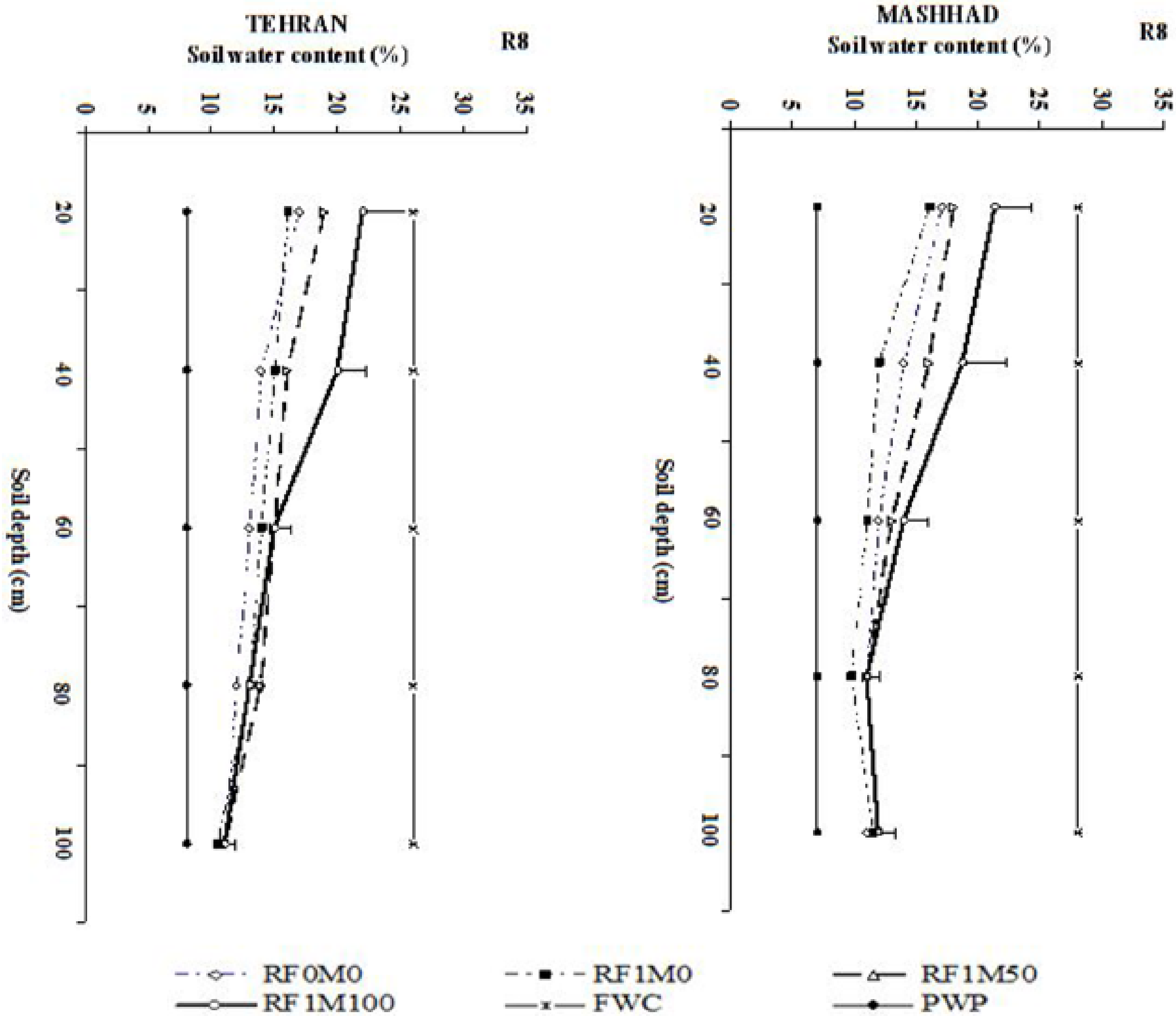

Fig. 5. Soil water content affected by different treatments at R8 sunflower growth stage in (left) Tehran and (right) Mashhad. RF_0M_0, neither ridge-furrow planting system nor wheat straw mulching; RF_1M_0, ridge-furrow planting system without wheat straw mulching; RF_1M_{50}, ridge-furrow planting system with wheat straw mulching only covering 50% of the soil surface; RF_1M_{100}, ridge-furrow planting system with full coverage (100%) of the soil surface with wheat straw mulch. PWP and FWC stand for the permanent wilting point and field water capacity, respectively. Bars stand for LSD at 0.05 levels.

and evaporation are high; moreover, there is often less rainwater in the sunflower growing season. In ridge-furrow planting system, application of wheat straw mulch increased SWC and SWS (Fig. 2–6). On average, treatments with mulch caused the greatest SWC and SWS during the whole growth period. Compared with RF_0M_0, RF_1M_{100} treatment significantly increased SWS. Higher soil moisture in straw-mulched treatments resulted in a slow response of soil temperature to increased air temperatures

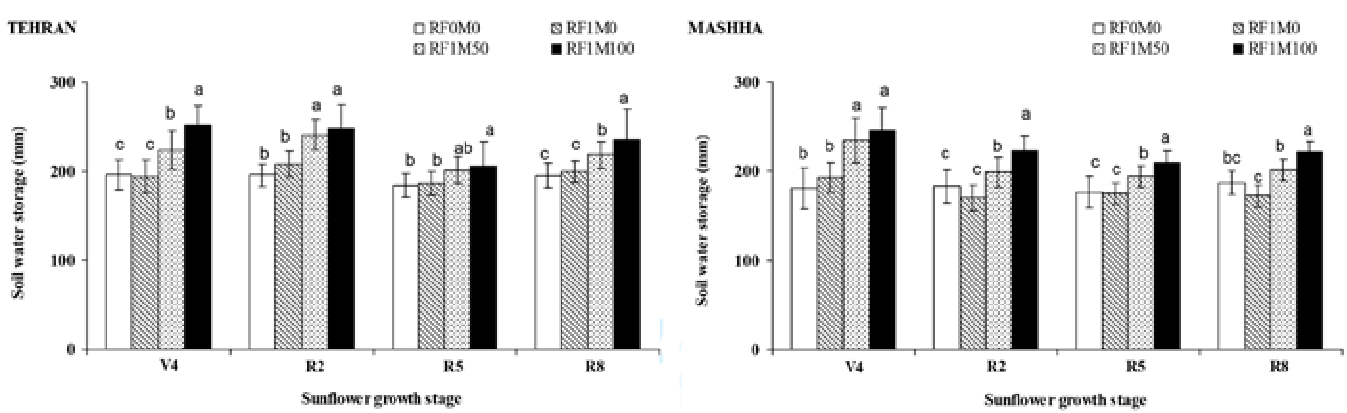

Fig. 6. Effect of treatments on soil water storage at different sunflower growth stages in (left) Tehran and (right) Mashhad. Means within each growth stage of each site followed by the same letter are not significantly different ($p \leq 0.05$). Bars show standard error.

Table 1. Mean comparisons of treatments on soil traits.

Year	Site	Treatment	MBC†	SOC‡	SMQ§
			mg kg^{-1}	g kg^{-1}	%
2014	Tehran	RF_0M_0¶	11.98c#	5.25c	2.29b
		RF_1M_0	12.20c	5.54c	2.21b
		RF_1M_{50}	35.44b	7.18b	4.93a
		RF_1M_{100}	42.23a	8.78a	4.80a
		LSD	4.33	0.81	1.02
	Mashhad	RF_0M_0	12.12c	5.12c	2.36b
		RF_1M_0	11.88c	5.36c	2.22b
		RF_1M_{50}	36.05b	7.35b	4.91a
		RF_1M_{100}	43.22a	8.98a	4.82a
		LSD	6.49	0.88	1.72
2015	Tehran	RF_0M_0	11.58c	5.44c	2.29b
		RF_1M_0	11.78c	5.26c	2.25b
		RF_1M_{50}	34.88b	7.63b	4.57a
		RF_1M_{100}	44.25a	9.08a	4.88a
		LSD	8.43	1.22	1.45
	Mashhad	RF_0M_0	12.25c	5.28c	2.32b
		RF_1M_0	12.56c	5.17c	2.42b
		RF_1M_{50}	35.68a	7.32b	4.88a
		RF_1M_{100}	42.35a	8.86a	4.78a
		LSD	6.89	1.09	1.92

† MBC: Microbial biomass carbon.

‡ SOC: Soil organic carbon.

§ SMQ: Soil microbial quotient.

¶ RF_0M_0: Without ridge-furrow planting system or wheat straw mulching; RF_1M_0: ridge-furrow planting system without wheat straw mulching; RF_1M_{50}: ridge-furrow planting system with wheat straw mulching only covering 50% of the surface by wheat straw mulch; RF_1M_{100}: ridge-furrow planting system with full (100%) wheat straw mulching.

In each column, the same small letters show no significant difference between treatments within a year and a site.

and solar radiation due to the increased soil heat capacity that accompanied the higher moisture contents (Gan et al., 2013). The straw mulching also protects the soil surface against direct sunlight and reduces soil radiation absorption (Chen et al., 2007). A lower topsoil temperature due to mulch application compared with mulch-free treatments implies a reduction in the energy available for vaporizing water from the soil surface (Singh et al., 2016). A significant and negative correlation between topsoil temperature and SWS (r^2 in Tehran = −0.75**, r^2 in Mashhad = −0.74**) supported this hypothesis. It should be noted that with the increase in mulch mass, the effects were more obvious. Furthermore, the absorption capability of the straw provides additional pathways for water infiltration (Li et al., 2011). This trapped water in the straw is gradually released over several days, resulting in decreasing the velocity of surface flow and increasing infiltration. Huang et al. (2005) and Liu et al. (2010) also suggested that mulch application could increase the soil water content and reduce drought problems during the wheat-growing season. The results from the present study provide direct support for this, as wheat straw mulch reached 100%, which was effective in controlling soil temperature and water retention.

In the present study, wheat straw mulch increased the soil properties including SOC, MBC, and SMQ (Table 1), which is supported by the results of other crop mulch research (Bandick and Dick, 1999; Blanchart et al., 2006). The increase in SOC in the ridge-furrow farming system accompanied by wheat straw mulching is mainly due to increased SOC derived from crop residues (Cherr et al., 2006). Soil MBC and SMQ are sensitive indicators of microbial activity and reflectors of soil quality (Benintende et al., 2008). It has been stated that soil moisture plays a crucial role in the level of soil MBC and SMQ, and this is of particular importance in semiarid environments (Li et al., 2004). Significant and positive correlation between MBC and SWS (r^2 in Tehran = 0.54*, r^2 in Mashhad = 0.62**) and between SMQ and SWS (r^2 in Tehran = 0.70**, r^2 in Mashhad = 0.78**) were found in support of this claim. In a study by Zhou et al. (2009), MBC was at the highest in mulched ridge treatment where topsoil moisture content was also the highest.

The application of wheat straw mulch significantly enhanced growth rate, increased seed number per capitule, seed weight, and harvest index, especially with full mulch cover (Table 2). Increase in crops yield due to straw mulch application has been previously reported in many studies (Bu et al., 2013; Chen et al., 2007; Gan et al., 2013). In a study, Li et al. (2001) stated that ridge-furrow mulching system hastens maize seed germination and seedling emergence by 2 d and promotes seedling growth compared with control. Similarly, Singh et al. (2016) observed that wheat plants grown under ridge-furrow mulching system had a 30% higher grain yield when compared with that in flat tillage without straw mulch. The increase in sunflower yield on account of ridge-furrow planting system and wheat straw mulching may be attributed to two factors: (i) water; wheat straw mulch directly inhibits evaporation of water from the soil surface (Chen et al., 2019), promotes water movement from deeper soil layers to the topsoil by vapor transfer (Jiménez et al., 2017), and enhances the topsoil water content during critical stages of crop growth (Liu et al., 2010); (ii) soil temperatures; the mixed effects of changes in surface and albedo roughness, higher water content and increased plant cover at the soil surface can lead to the lower soil temperature under straw mulching (Buerkert et al., 2000). Moreover, in midsummer, when the air temperature becomes high, and heat stress may become an issue for sunflower growth and development, wheat straw mulch reduces the soil temperature significantly compared with control treatment. Studies have shown that lower soil temperature postponed root senescence (Bu et al., 2013; Li et al., 1999) and promoted crop root growth (Pandey et al., 2015). Plant leaf senescence is also closely related to root growth (Kante et al., 2016). So, it is not surprising that higher seed yield associates with mulch application.

CONCLUSION

This study compared the effects of ridge-furrow planting system associated with different wheat straw mulching treatments on various aspects of sunflower production under semiarid climatic conditions. The results herein clearly indicate that the application of ridge-furrow planting system with full (100%) wheat straw mulching was considerably more effective than the control treatment or ridge-furrow planting system with 50% wheat straw mulching for improving most quantitative sunflower traits. In addition, straw mulch moderates soil temperature in the hot summer, preventing the topsoil from reaching temperatures that inhibit plant growth. On the other hand, the combination of mulching with ridge furrowing is an advanced step in increasing soil water availability. It was also found that application of crop mulch such as wheat straw mulching improved soil properties such as soil MBC, SOC, and SMQ.

Table 2. Mean comparisons of treatments on yield components and seed yield.

Year	Site	Treatment	Capitule density	Seed no.	1000-seed weight	Final dry matter	Seed yield	Harvest index
			no. m^{-2}	no.capitule^{-1}	g	kg ha^{-1}		%
2014	Tehran	RF_0M_0†	5.1a‡	1538c	122c	3457b	1309d	38b
		RF_1M_0	4.9a	1555c	124c	3543b	1382c	39ab
		RF_1M_{50}	5.5a	1659b	139b	3516b	1512b	43a
		RF_1M_{100}	5.2a	1735a	152a	3940a	1625a	41ab
		LSD	0.84	56	8.44	106	67	3.21
	Mashhad	RF_0M_0	5.5a	1542c	124c	3330b	1367c	41b
		RF_1M_0	5.5a	1551c	125c	3392b	1391c	41b
		RF_1M_{50}	5.5a	1667b	140b	3366b	1515b	45a
		RF_1M_{100}	5.5a	1789a	154a	3852a	1632a	42b
		LSD	0.49	74	4.91	131	81	2.46
2015	Tehran	RF_0M_0	5.5a	1532c	119c	3320c	1288d	39b
		RF_1M_0	5.5a	1547c	123c	3663a	1392c	38b
		RF_1M_{50}	5.5a	1679b	138b	3355c	1510b	45a
		RF_1M_{100}	5.5a	1791a	150a	3558b	1627a	46a
		LSD	0.19	63	7.23	64	66	3.11
	Mashhad	RF_0M_0	5.5a	1554c	121c	3394d	1309d	39ab
		RF_1M_0	5.5a	1546c	122c	3686b	1401c	38b
		RF_1M_{50}	5.5a	1648b	141b	3527c	1517b	43a
		RF_1M_{100}	5.5a	1758a	153a	3997a	1631a	41ab
		LSD	0.46	73	6.19	89	89	2.84

† RF_0M_0: Without ridge-furrow planting system or wheat straw mulching; RF_1M_0: ridge-furrow planting system without wheat straw mulching; RF_1M_{50}: ridge-furrow planting system with wheat straw mulching only covering 50% of the surface by wheat straw mulch; RF_1M_{100}: ridge-furrow planting system with full (100%) wheat straw mulching.

‡ In each column, the same small letters show no significant difference between treatments within a year and a site.

Our results revealed that covering the soil with wheat straw could be a beneficial approach for decreasing heat and water stress and improving the sustainability of agricultural systems.

SUPPLEMENTAL MATERIAL

Table S1. Soil physical and chemical properties.

Table S2. Mean comparisons of treatments on days and growing degree days.

Fig. S1. Average monthly temperature and precipitation of the growing seasons (2014 and 2015) and long-term (30-yr) in Tehran (left) and Mashhad (right).

ACKNOWLEDGMENTS

This research was supported financially by the Iran National Elites Foundation and Seed and Plant Improvement Institute (Memorandum no.: 15/79547 and Letter no.: 15/79894).

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