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RESEARCH ARTICLE

Effects of combined drip irrigation and mulching practices on the soil evaporation characteristics in a young apple orchard in arid northwestern China

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KEYWORDS

Drip irrigation, orchards soil evaporation, surface mulching, water-limited regions

HIGHLIGHTS

- Effects of the combination of drip irrigation and mulching practices on SE characteristics in a young orchard were investigated.
- Mulching treatments significantly affected daily SE and SWCs dynamics of the young orchard.
- Daily SE under FM and SM treatments was more susceptible to be affected by meteorological factors.
- SM is considered to be a more effective mulching practice for reducing unproductive SE and improving SWC status in young orchard with DI.

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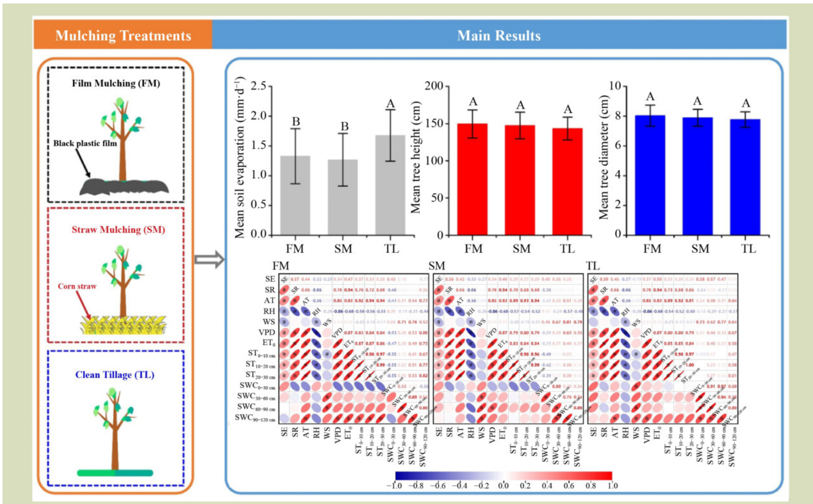
GRAPHICAL ABSTRACT



ABSTRACT

Soil evaporation (SE) is a key component of regional hydrological balance, especially in arid areas. China has the largest area of apple orchards in the world, but the effects of mulching practices on SE dynamics and their controlling factors remain poorly understood in orchards using drip irrigation (DI). This study was conducted to address these issues by measuring SE, meteorological factors, soil temperature (ST), and soil water content (SWC) in young apple orchard under two mulching treatments during the growing season. Field experiments, which included three treatments—film mulching (FM) and maize straw mulching (SM), and clean tillage (TL) as a comparator—were conducted in 3-year-old apple orchard with DI in arid northwestern China. The results revealed that mulching significantly affected the daily SE dynamics of the young orchard ($p < 0.05$), and the daily mean SE under FM, SM, and TL treatments was about 1.3 ± 0.5, 1.3 ± 0.4, and 1.7 ± 0.4 $mm \cdot d^{-1}$, respectively. No significant differences were detected in the daily

SE between FM and SM treatments ($p > 0.05$), whereas the daily SWC in the four soil layers to 120 cm were consistently greater under SM treatment than under FM and TL treatments ($p < 0.05$). Compared to the TL treatment, the daily SE under FM and SM treatments was more susceptible to meteorological factors. Stepwise regression analysis showed that the daily SE of the young orchard was mainly controlled by the vapor pressure deficit, reference evapotranspiration and solar radiation, regardless of the treatment. However, there was no significant relationship between the daily SE and wind speed under TL treatment ($p > 0.05$). This study highlighted the significant differences in SE losses and SWC dynamics of the mulching treatments. Overall, SM is considered to be a more effective mulching practice for reducing unproductive SE and improving SWC status in young apple orchards with DI in arid and similar climatic regions.

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1 Introduction

Apple trees are adapted to various climates and are among the most widely cultivated fruit crops globally[1,2]. China has become the largest apple producer in the world, accounting for the largest planting area (2.1×10^6 ha, 43%) and total production of apples (4.6×10^7 t, 49%) in 2021[3]. The Loess Plateau is one of the two main apple production areas in China due to its abundant sunlight, good ventilation and large diurnal temperature differences[4]. This area has a dry climate, so water is a scarce resource especially in arid areas where most crops are grown under irrigation[5,6]. Compared to many other agricultural crops, apple trees have high levels of evapotranspiration (ET)[7–9], and a shift from field crops into apple orchards can increase soil water consumption and influence soil water content (SWC)[4]. In addition, inefficient irrigation practices and changing climate conditions further exacerbate the imbalance between water supply and demand in the apple industry particularly in water-limited regions. Consequently, this has negative effects on apple production. Thus, water-efficient technologies and sound water management practices are clearly needed for the sustainable development of the apple industry in arid areas[10,11].

As a modern water-efficient irrigation technique, drip irrigation (DI) is viewed as a solution to the conflicts between agricultural and ecological water needs in water-limited regions[12,13]. Su et al.[14] found that ET of apple trees with DI increased with increasing irrigation amount and that the crop coefficient was much lower than with surface irrigation. Li et al.[15] reported that the soil water storage and water use efficiency of a 6-year-old apple orchard with DI were consistently greater than those with furrow irrigation. Lecaros-Arellano et al.[2] emphasized that variations in wetting patterns under different DI treatments caused significant differences in yield and quality of apples. Although DI has many advantages over other irrigation methods, it is still inevitable that a certain wet areas will occur in the surface soil around the emitter. The formation of these wet areas will allow more water to be lost through soil evaporation (SE)[16,17]. Compared to transpiration, SE has distinctly different functions within ecosystems: SE does not directly contribute to production and is commonly considered an undesirable component[18,19]. Previous studies have focused mainly on ET dynamics and water use efficiency in apple orchards with different irrigation techniques[5,10,20], whereas little information is known about SE dynamics in apple orchards with DI and its relationships with bio-abiotic influencing factors. An improved understanding of SE characteristics in apple orchards with DI is thus critical for choosing appropriate water conservation practices and fully exploiting the productive potential of apple orchards especially in water-limited regions.

Surface mulching is commonly used as a water conservation practice in arid and semiarid areas, and the effects of mulching practices on soil water status and fruit yield differ[21–23]. Suo et al.[24] found that different mulching practices improved the SWC, water use efficiency and yield in apple orchards on the Loess Plateau, with the greatest effect being achieved with gravel or straw mulching (SM). Liao et al.[25] investigated the effect of mulching on soil infiltration and SE in apple orchards and found that by increasing soil infiltration and reducing SE, surface mulching can improve the soil environment and yield of apple orchards in semiarid areas. SE can also be the major ET component because most plants have incomplete canopy cover at some growth stages[26–28]. Tree age clearly affected ET partitioning of apple orchards due to the morphology of the trees, and an earlier study revealed that annual SE accounted for the largest proportion of ET (51.7% to 53.6%) in a 7-year-old apple orchard[4]. Considering the increasing planted area and sparse vegetation cover, the significant effects of undesirable SE losses in young apple orchards on local- and catchment-scale water balances should not be ignored. The combination of irrigation techniques and mulching practices has a complex effect on the soil moisture, heat and yield of apple orchards[29–31], whereas few studies have investigated the effects of the combination of DI and different mulching practices on SE dynamics and their controlling factors in young apple orchards in arid areas. Therefore, it is necessary to explore SE characteristics in young apple orchards served by a combination of DI and mulching practice in water-limited regions.

In this study, we measured SE, SWC, and soil temperature (ST) of a 3-year-old apple orchard with DI, which included three mulching practices, during the 2021 growing season in arid, northwestern China. The primary objectives of this study were to: (1) quantify and compare the effects of the combination of DI and different mulching practices on SE dynamics and plant growth in a young apple orchard, and (2) explore and evaluate the relationships between SE in a young apple orchard and the influencing factors between different treatments. The data generated should provide a deeper understanding of the effects of the combination of DI and mulching practices for on the SE characteristics of young apple orchards especially in arid areas.

2 Materials and methods

2.1 Site description

This experiment was conducted at Shiyanghe Experimental Station (China Agricultural University) located in Wuwei (Gansu Province) in northwestern China (37°51′ N, 102°52′ E; 1581 m above sea level). The study area has a continental temperate arid climate, with an average annual temperature of 8 °C. The mean annual sunshine hours exceed 3000 h, and the annual average cumulative temperature is more than 3550 °C[32]. Water resources are scarce in this region, with an annual precipitation of 164 mm. The mean annual pan evaporation is about 2000 mm and the groundwater depth ranges from 40 to 50 m. The soil in this region is sandy loam, and the average dry soil bulk and mean field capacity at 0 to 120 cm deep are about 1.46 g·cm^{-3} and 0.30 cm^3·cm^{-3}, respectively[6].

A field of about 0.4 ha with 370 apple trees was chosen for this experiment. The trees (*Malus domestica* cv. Fuji) were about 3 years old in 2021, with rowing space of 3.0 m and interplant spacing of 4.0 m arranged in an east–west orientation, and irrigation of 250 mm over the full growing season[5]. Irrigation water was obtained from a well near the experimental site, and the total rainfall amount during the study period was about 105 mm. Irrigation (DI with two lines per row and 0.3 m emitter spacing) was applied three times (Fig. 1) on days determined by orchard management and environmental conditions[33]. This experiment consisted of three treatments: film mulching (FM), maize SM, and clear tillage (TL) as a comparator. For each treatment, there were three replicate plots of 41 or 42 apple trees. A 10-cm deep and 120-cm wide ditch was dug along both sides of the tree row in the FM

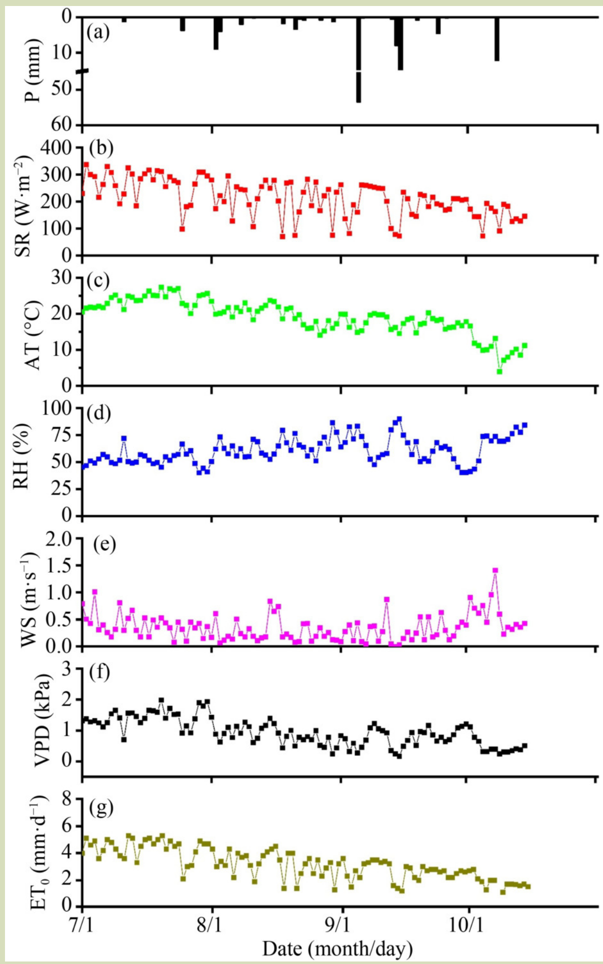

Fig. 1 Seasonal variations in precipitation (P) (a), solar radiation (SR) (b), air temperature (AT) (c), relative humidity (RH) (d), wind speed (WS) (e), vapor pressure deficit (VPD) (f), and reference evapotranspiration (ET_0) (g) during the study period.

treatment, and black plastic film with a thickness of 50 μm was used for mulching. Maize straw cut 25–30 cm long was applied in the SM treatment. Both sides of the tree row were covered with maize straw to a thickness of 10 cm. The straw was obtained from a maize field near the orchard and was exposed to the sun for 3–5 days before being applied[25]. The TL treatment received regular hand weeding and no surface mulching.

2.2 Meteorological factors, SWC, and ST

Meteorological data sets were continuously recorded by an automatic weather station in a grassy area 100 m from the experimental orchard. The meteorological measures included precipitation (P), solar radiation (SR), air temperature (AT), relative humidity (RH), and wind speed (WS). Vapor pressure deficit (VPD) was calculated from AT and RH[34]. Reference ET (ET_0) was calculated using the Penman-Monteith formula recommended by FAO[35].

Soil samples were collected to a depth of 120 cm in each treatment using a soil auger. SWC of the samples was determined by the oven-drying[36], and SWC was monitored at approximately 10-d intervals. SWC was measured at 10 cm intervals to 120 cm deep and the sample sites were distributed within and between rows. A total of 12 sites were selected on each sampling date in each treatment, and the daily SWC for each treatment was averaged for four layers: 0–30, 30–60, 60–90, and 90–120 cm.

ST was measured using an angle-stem earth thermometer at fixed times (08:00, 14:00 and 20:00), and the measurement of ST was postponed one or two days on rainy or irrigation days. For each treatment, ST was measured in the 0–30 cm layer of three randomly selected sample sites. The thermometer inserted placed at each site at depths to 5, 10, 15, 20, and 25 cm deep. The mean of 45 (3 × 3 × 5) ST measurements from the 0–30 cm layer recorded in a day was used as the daily ST for each treatment on that day.

2.3 SE measurement

SE was measured using microlysimeter of 20 cm in height and 10 cm in diameter. The microlysimeters were constructed from PVC pipe, and each microlysimeter consisted of an inner cylinder and an outer cylinder to prevent potential fluctuations in temperature and the flux of energy between the soil inside and outside the lysimeter[37]. A handle was attached to the inner cylinder to facilitate its periodic extraction from the outer cylinder. The inner cylinder was slowly hammered into the plots, filled with undistributed soil, and then inserted into larger PVC cylinders previously installed in the sample plots. The inner cylinder was then packed with gauze at the bottom.

The microlysimeters were covered with a mulch layer in the mulched treatments[25]. The soil inside the microlysimeters was replaced every 5–7 d and after a heavy rain or irrigation event. A total of 15 microlysimeters were randomly installed in each treatment. The inner cylinder was weighed each day at 08:00 using a portable balance (± 0.1 g) and was placed back into the outer cylinder. Daily SE (mm·d^{-1}) for each treatment was calculated as:

$$\mathrm{SE} = 10 \times \sum_{i=1}^{n} \frac{\Delta w/\rho}{n\pi(D/2)^2} \tag{1}$$

where, Δw is the difference between the two inner cylinder weights (g) in 24 h, ρ is the density of water (g·cm^{-3}), n is the number of microlysimeters in each treatment (n = 15), and D is the diameter of the inner cylinder (cm).

2.4 Tree height and tree diameter

Tree height (TH, cm) was measured using a meter ruler and tree diameter (TD, cm) was determined using Vernier calipers (Model 7D-01150; Forgestar Inc., Shanghai, China). TH and TD of the young orchard were measured in 12 randomly selected trees for each treatment. All selected trees were from inner rows and not at the ends of rows to eliminate edge effects. The mean TH and TD measurements from the 12 selected trees recorded in a day were used as the daily TH and TD for each treatment on that day, respectively.

2.5 Data analyses

Summary statistics, such as the means, standard deviations and coefficients of variation (CVs) of meteorological factors, SWC, ST, TH, TD, and SE for each treatment were calculated. One-way analyses of variance were used to evaluate the statistical differences of TH, TD, and SE between the treatments and to compare SWC and ST between the soil layers and treatments. Pearson correlation analyses were used to determine the significance of the relationships of daily SE with the influencing factors for each treatment. Multivariate stepwise linear regression was used to further determine the strength of the relationships between daily SE and the influencing factors. The level of significance was set at a confidence interval of 95%, and all the statistical analyses were performed using SPSS 16.0 (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Meteorological factors, SWC, and ST

As shown in Fig. 1, daily P, SR, AT, RH, WS, VPD, and ET_0 had obvious seasonal variations during 2021. Daily P, SR, AT, RH, WS, VPD, and ET_0 ranged from 0.2 to 53.4 mm (5.9 ± 11.7 mm), 70.9 to 337 W·m^{-2} (215 ± 68.3 W·m^{-2}), 4.0 to 27.4 °C (19.4 ± 4.8 °C), 40.3% to 90.1% (60.9% ± 11.8%), 0.1 to 1.4 m·s^{-1} (0.4 ± 0.2 m·s^{-1}), 0.2 to 1.9 kPa (0.9 ± 0.4 kPa) and 1.1 to 5.3 mm·d^{-1} (3.2 ± 1.1 mm·d^{-1}), respectively, with CVs of 197%, 31.8%, 25.2%, 19.4%, 70.1%, 46.8%, and 35.5%, respectively. The highest monthly mean meteorological factors generally occurred in July or August. During the study period, 21 rainfall events were recorded with a cumulative gross precipitation of 124 mm.

During the study period, the daily SWCs under the treatments exhibited different patterns (Fig. 2). Daily SWC at the upper layers under TL treatment was lower than under FM and SM treatments, and daily $SWC_{0\text{–}30\ cm}$ under FM, SM and TL ranged from 10.4 to 11.4, 10.7 to 11.6, and 9.2 to 9.9 cm·cm^{-3}, respectively. In each treatment, daily SWC at the lower layers fluctuated little whereas there were significant differences between the treatments in daily SWC particularly in the 70–90 cm layer. The daily $SWC_{70\text{–}90\ cm}$ under FM, SM and TL treatments ranged from 17.6 to 18.9, 18.5 to 19.2, and 17.8 to 19.0 cm^3·cm^{-3}, respectively, with CVs of 2.3%, 1.3%, and 1.9%, respectively.

The daily ST in different soil layers varied seasonally with similar patterns in each treatment (Fig. 3). The daily ST in the 0–10 cm layer was consistently higher than that in the 10–20 cm and 20–30 cm layers, regardless of the mulching treatments. During the study period, the daily $ST_{0\text{–}10\ cm}$ under FM, SM, and TL treatments ranged from 11.8 to 36.9, 10.3 to 31.2, and 9.2 to 35.7 °C, respectively, with means of 27.0 ± 6.1, 23.0 ± 4.8, and 24.9 ± 6.6 °C, respectively. The daily ST throughout the soil profile was lower under SM treatment than under FM and TL treatments. The daily ST at 10–20 and 20–30 cm layers under SM treatment ranged from 10.6 to 28.6 (21.5 ± 4.3) and 10.7–30.0 (21.8 ± 4.7) °C, respectively, with CVs of 20.1% and 21.7%, respectively.

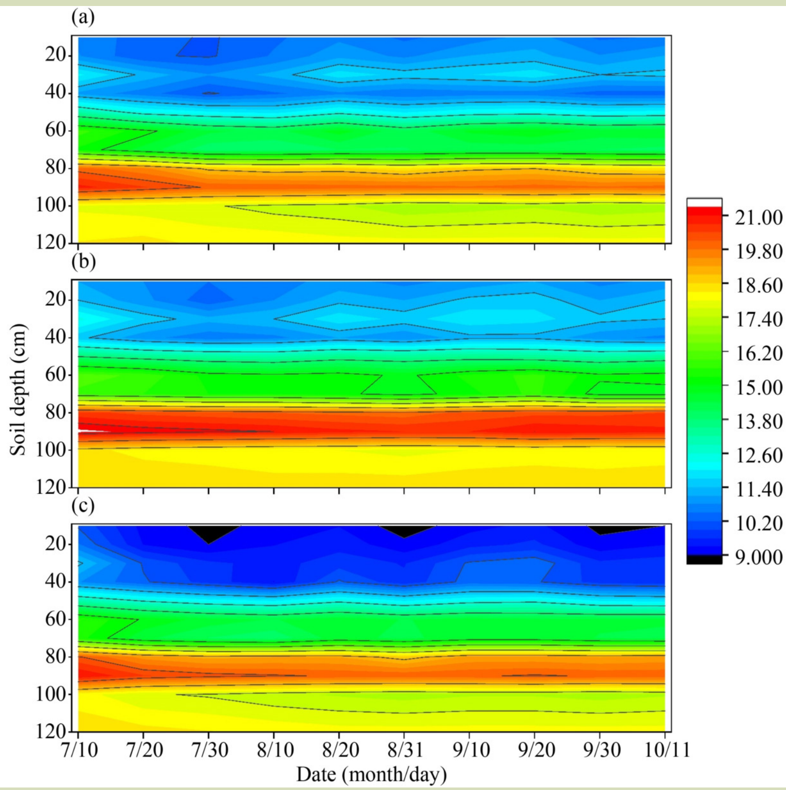

Fig. 2 Daily soil water content (SWC) throughout the 120-cm soil profile under different treatments of film mulching (FM) with drip irrigation (DI) (a), maize straw mulching (SM) with DI (b), and clear tillage (TL) with DI (c) during the study period.

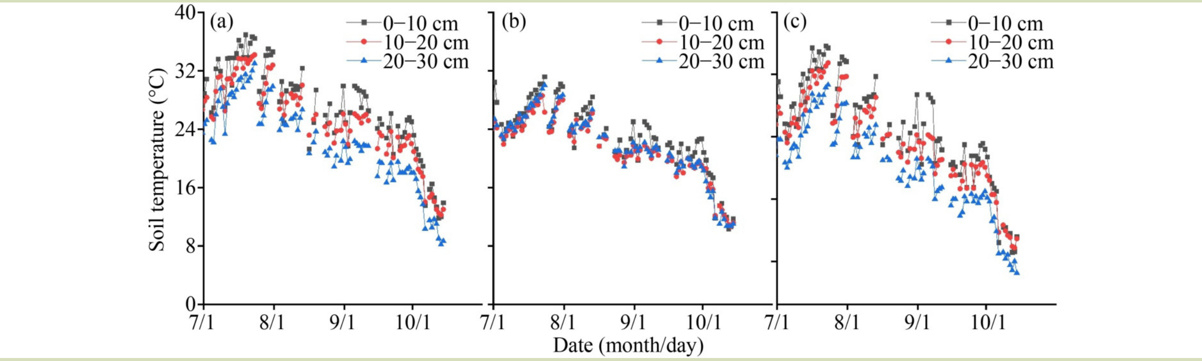

Fig. 3 Daily soil temperature (ST) in the 0–30 cm soil layer under different treatments of film mulching (FM) with drip irrigation (DI) (a), maize straw mulching (SM) with DI (b), and clear tillage (TL) with DI (c) during the study period.

3.2 Dynamics of SE and plant growth under different treatments

During the study period, the trends of daily SE in the three treatments were similar (Fig. 4). The daily SE of the young orchard under FM, SM, and TL treatments ranged from 0.3 to 2.3, 0.2 to 2.2, and 0.6 to 2.6 mm·d^{-1}, respectively, with CVs of 34.8%, 34.7%, and 25.7%, respectively. The mulching treatments clearly affected the dynamics of SE and daily SE of the young orchard under FM and SM treatments was significantly lower than under TL treatment (p < 0.05) (Fig. 5). There was no significant difference in daily SE between FM and SM treatments (p > 0.05). The mean daily SE of the young orchard under FM, SM, and TL treatments were 1.3 ± 0.5, 1.3 ± 0.4, and 1.7 ± 0.4 mm·d^{-1}, respectively. Eighty-seven daily SE data points were collected in each treatment and the total SE of the young orchard under FM, SM, and TL treatments were about 116, 110, and 146 mm, respectively.

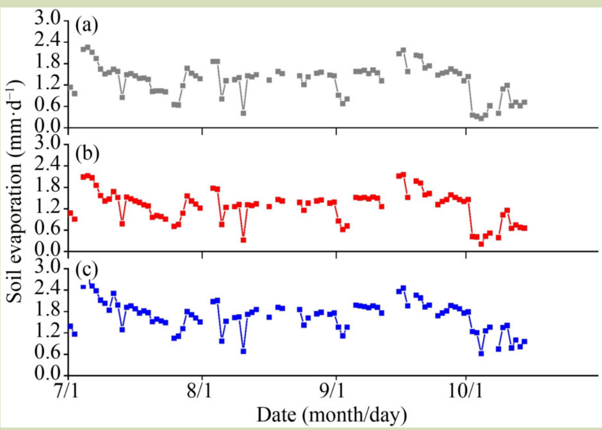

Fig. 4 Dynamics of daily soil evaporation (SE) of a young apple orchard under different treatments of film mulching (FM) with drip irrigation (DI) (a), maize straw mulching (SM) with DI (b), and clear tillage (TL) with DI (c) during the study period.

The daily TH and TD of the young orchard had obvious seasonal variation between treatments (Fig. 6). The daily TH and TD under TL treatment were consistently lower than under FM and SM treatments, whereas there was no significant difference in the daily TH (TD) between the treatments (p > 0.05) (Fig. 5). The daily TH and TD under TL treatment ranged from 114 to 158 (143 ± 15.2) cm and 6.8 to 8.4 (7.8 ± 0.5) cm, respectively, with CVs of 10.6% and 6.7%, respectively. Daily TH under FM and SM treatments ranged from 114 to 168 and 114 to 165 cm, respectively, with means of 149.6 ± 18.9 and 147.5 ± 17.8 cm, respectively. The corresponding daily TD values ranged from 6.8 to 8.9 (8.0 ± 0.7) and 6.9 to 8.5 (7.9 ± 0.6) cm, respectively, with CVs of 8.8% and 7.2%, respectively.

3.3 Correlations between SE and influencing factors under different treatments

The correlations between the daily SE of the young orchard and the influencing factors differed between the treatments, as shown in Fig. 7. The variations in the daily SE in each treatment were significantly affected by meteorological factors such as SR, AT, and VPD, but there was no significant relationship between daily SE and WS under TL treatment (p > 0.05). Compared to the TL treatment, daily SE of the young orchard under FM and SM treatments was more susceptible to be affected by meteorological factors. The daily SE in each treatment was significantly correlated with daily ST in the different soil layers (p < 0.05), whereas no significant relationships occurred between daily SE and SWC throughout the soil profile, regardless of the mulching treatment (p > 0.05). The stepwise regression equations between daily SE and the

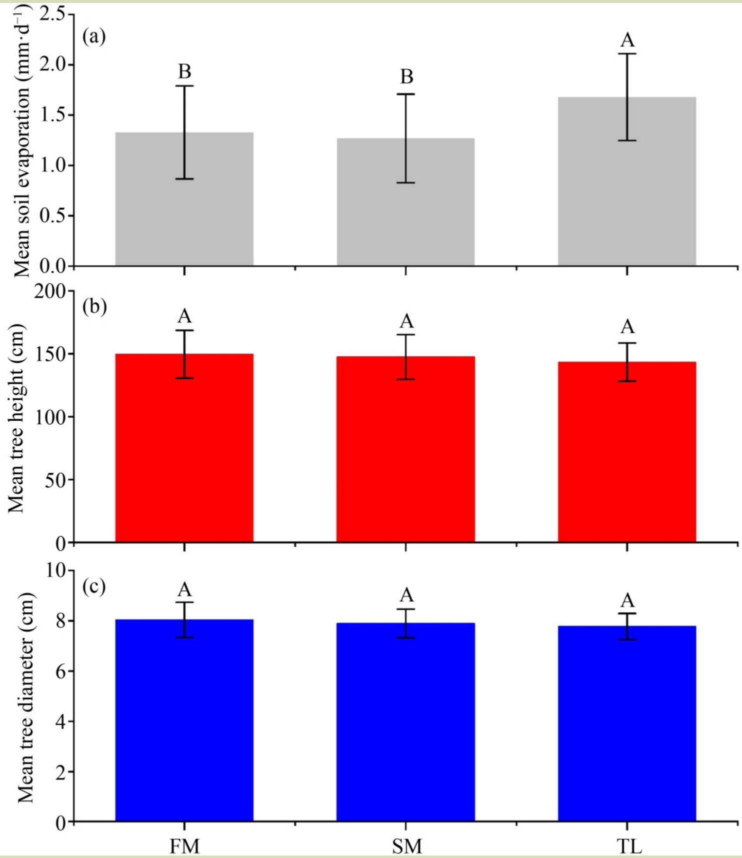

Fig. 5 Comparison of mean daily soil evaporation (SE) (a), tree height (TH) (b), and tree diameter (TD) (c) in a young apple orchard under different treatments of film mulching (FM) with drip irrigation (DI), maize straw mulching (SM) with DI, and clear tillage (TL) with DI during the study period. Bars with the letter are not significantly differences in daily SE, TH, and TD between treatments ($p < 0.05$).

influencing factors also differed between the treatments (Table 1). The daily SE of the young orchard was mainly controlled by VPD, ET_0, and SR in all treatments.

The mean daily ST and SWC throughout the soil profile differed between the treatments (Fig. 8). During the study period, the daily $ST_{0–10\ cm}$ was consistently higher than daily $ST_{10–20\ cm}$ and daily $ST_{20–30\ cm}$ ($p < 0.05$) in each treatment. At the same depth, the daily ST under FM treatment was significantly higher than under SM and TL treatments ($p < 0.05$). Compared to the FM treatment, the effects of SM treatment on daily ST throughout the soil profile were weak. There was no significant difference in daily $ST_{0–10\ cm}$ between SM and TL treatments ($p > 0.05$). The daily SWC of the young orchard was consistently higher under SM treatment than under FM and TL treatments ($p < 0.05$), whereas no significant differences in daily $SWC_{30–120\ cm}$ were detected between FM and TL treatments ($p > 0.05$). The daily SWC in 60–90 and 90–120 cm layers was significantly higher than that in the upper layers ($p < 0.05$) in each treatment.

The relationships between daily SE of the young orchard and ST in the different soil layers in each treatment are shown in Fig. 9. As daily ST in different soil layers increased, daily SE of the young orchard increased, peaked and then had a decreasing trend, regardless of the treatment. In each treatment, the threshold of daily ST in the soil layers also differed. The average threshold of daily ST for the whole soil profile under FM, SM, and TL treatments were about 26.2, 21.9, and 23.6 °C, respectively.

4 Discussion

4.1 SE dynamics under different treatments

In this study, the SE of a young orchard was measured using microlysimeters. Although replacing the soil in microlysimeters is considered to be time consuming and the method also cannot measure continuously during rain or

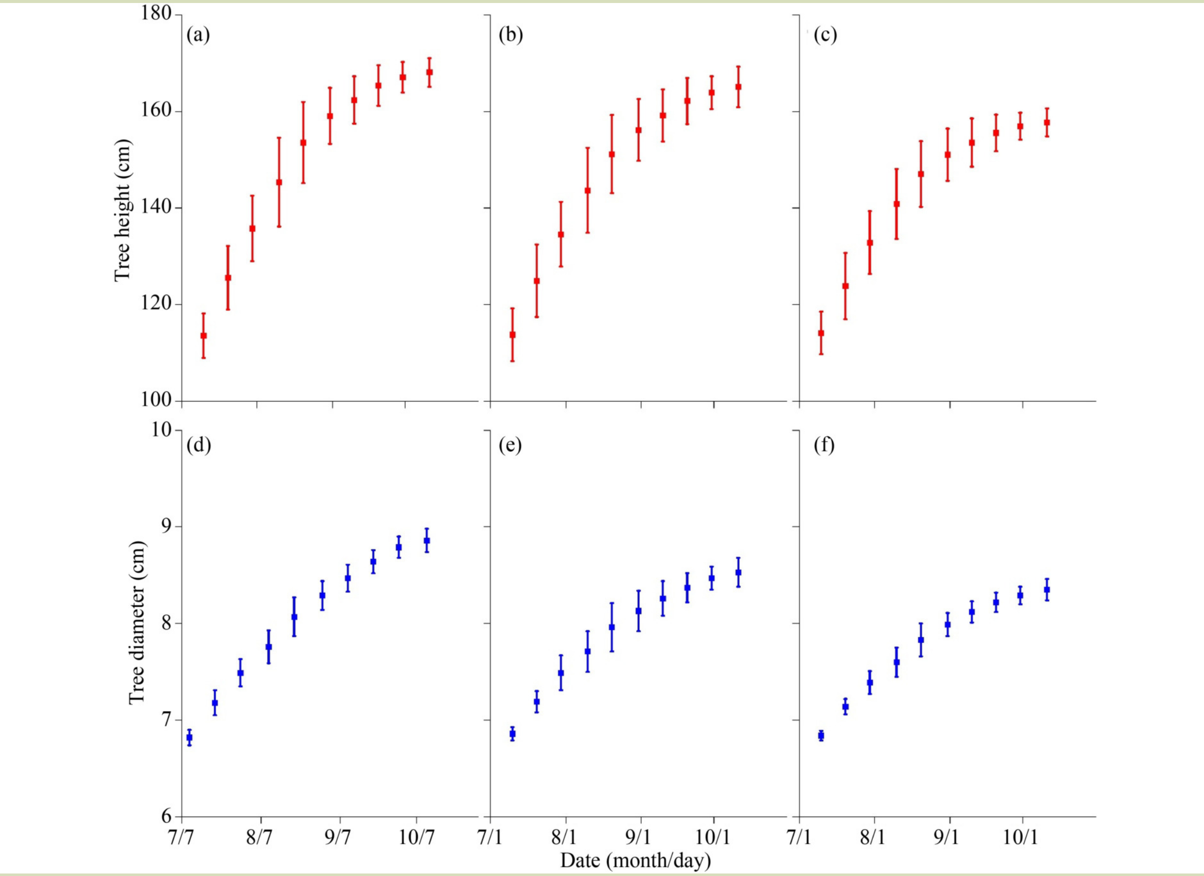

Fig. 6 Dynamics of tree height (TH) and tree diameter (TD) of a young apple orchard under different treatments of film mulching (FM) with drip irrigation (DI) (a and d), maize straw mulching (SM) with DI (b and e), and clear tillage (TL) with DI (c and f) during the study period.

irrigation due to the limitation of weighing frequency[18,28,38], microlysimeters are still the most widely used approach for field experiments[39–41]. In addition, many steps have been taken to improve the accuracy of SE measurements in the orchard during the study period. We thus consider that daily SE data obtained from the microlysimeters can be used to identifying differences between the treatments. Due to the COVID-19 pandemic, the measurements were collected only in 2021. Considering the sparse morphologies of the trees, changes in vegetation cover in this young orchard can be ignored over the next 1 or 2 years and there were also three separate replicates of each treatment. Therefore, we inferred that the data from the study period were also sufficient to form reliable conclusions. In addition, we found that other related field measurements, especially SE and/or SWC measurements were also conducted during one growing season. For example, Liao et al.[25] investigated SE characteristics of apple orchards in semiarid areas during the rainy season (June to August) and found that SM had a greater effect on reducing SE than horticultural fabric mulching. Nazari et al.[31] explored water use and root uptake under the soil in subsurface DI from July to October in 2018 and found that the highest and lowest root water uptake occurred at the distances 60 and 50 cm (radial and depth), and 150 and 75 cm from the tree trunk, respectively.

Our study found that mulching treatments clearly affected the dynamics of SE of a young orchard. The daily mean SE of the young orchard under FM, SM, and TL treatments was about 1.3 ± 0.5, 1.3 ± 0.4, and 1.7 ± 0.4 $mm \cdot d^{-1}$, respectively, suggesting that mulching significantly reduced unproductive SE water loss. Liao et al.[25] also found that compared to bare soil, the mean daily SE of an 8-year-old apple orchard in the energy-limited stage decreased by about 35% and 48% in FM and SM treatments, respectively, which are higher than the mean reduction in the relative evaporation rate under FM and SM treatments (24%) in our study. SE is mostly a result of abiotic processes and is collectively affected by meteorological factors, canopy shading and SWC conditions[26,42,43]. The three treatments were applied in the same orchard, so the differences

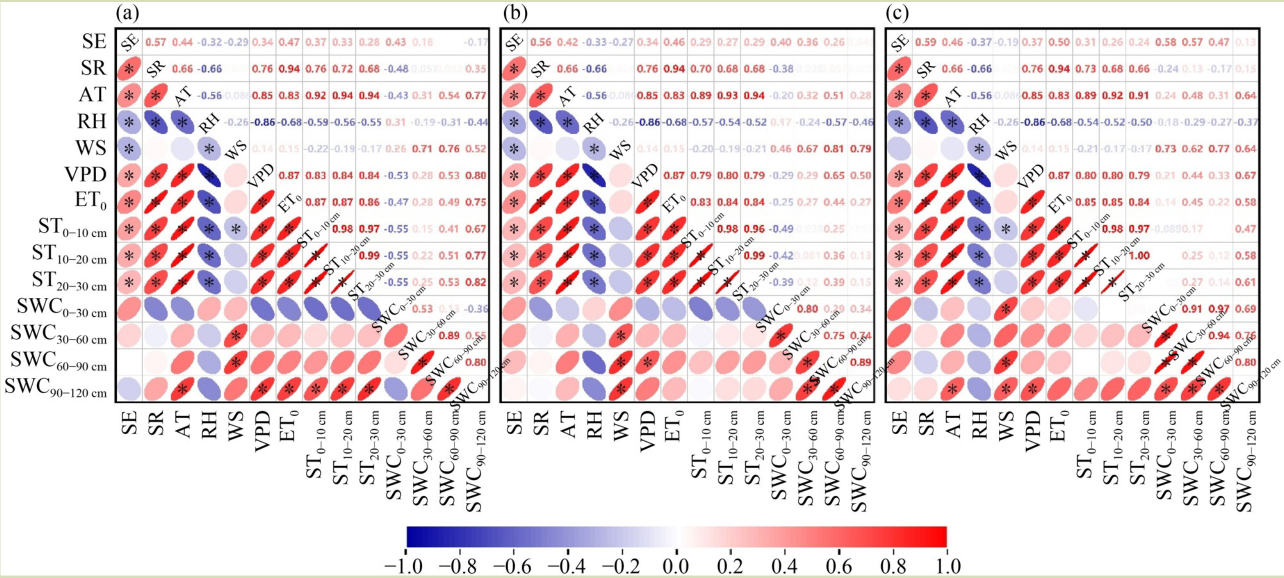

Fig. 7 Correlations between daily soil evaporation (SE) and the influencing factors under different treatments of film mulching (FM) with drip irrigation (DI) (a), maize straw mulching (SM) with DI (b), and clear tillage (TL) with DI (c). SR, AT, RH, WS, VPD, ET_0, ST, and SWC are solar radiation, air temperature, relative humidity, wind speed, vapor pressure deficit, reference evapotranspiration, soil temperature, and soil water content, respectively. *Indicates significance at 0.05 level.

Table 1 The stepwise regression equations between daily soil evaporation (SE) and the influencing factors under different treatments of film mulching (FM) with drip irrigation (DI), maize straw mulching (SM) with DI, and clear tillage (TL) with DI during the study period

Treatment	Regression equation	Adjust R^2	F value
FM	$SE = 0.687VPD - 0.700ET_0 + 0.013SR - 0.128$	0.407	25.3^{**}
SM	$SE = 0.668VPD - 0.684ET_0 + 0.013SR - 0.112$	0.416	22.4^{**}
TL	$SE = 0.876VPD - 0.837ET_0 + 0.015SR + 0.021$	0.418	19.4^{**}

of meteorological variables and canopy characteristics between treatments can be ignored. Local variations in near-surface radiation, wind conditions and ST are important for controlling SE[44–46], and different treatments might lead to differences in the characteristics of these variables and subsequently cause differences in daily SE. Our study found that the daily ST (SWC) throughout the soil profile differed between the treatments and daily ST in the different soil layers were positively correlated ($p < 0.05$) with daily SE in each treatment. SM treatment consistently reduced ($p < 0.05$) daily ST int different soil layers in a young orchard, which might have been caused by the thick isolation layer from maize straw, which contributed to regulation of solar reflectance, thermal conductivity and temperature dissipation for surface ST during the study period[47,48].

No significant differences were observed in daily SE of the young orchard between FM and SM treatments ($p > 0.05$), which was similar to the results of Zhang & Xie[49]. However, Liao et al.[25] found that the daily SE of an 8-year-old orchard was higher under FM treatment (0.87–1.37 mm·d^{-1}) than under SM treatment (0.67–1.11 mm·d^{-1}) in fruit expansion stage in semiarid areas. Previous studies have indicated that water and nitrogen use efficiency in arable dry lands increased under mulching compared to no mulch[24,50], whereas consistent conclusions have not been reached regarding the effects of mulching treatments on SE and/or water consumption in apple orchards. This is possibly related to the effects of mulching practice managements, soil texture and climate regime on variations of SE[24,45,51,52]. The selection of mulching materials and design of mulching thickness largely influenced the roughness and aerodynamic resistance of mulching layer to water vapor flow[53,54]. Chen et al.[46] explored effects of sand-mulch thickness on SE dynamics and

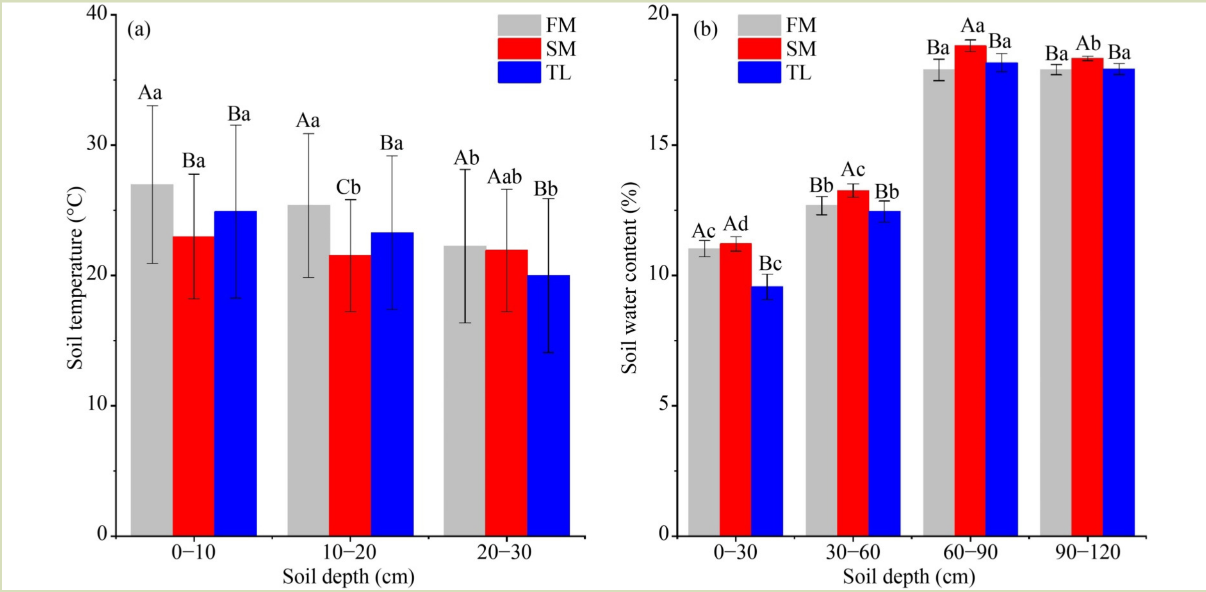

Fig. 8 Comparison of mean daily soil temperature (ST) (a) and soil water content (SWC) (b) at different depths in a young apple orchard under different treatments of film mulching (FM) with drip irrigation (DI), maize straw mulching (SM) with DI, and clear tillage (TL) with DI. Bars with the same uppercase letter are significantly different in ST and SWC between treatments for the same depth ($p < 0.05$). Those with the same lowercase letters are not significantly different in ST and SWC between depths for the same treatment ($p < 0.05$).

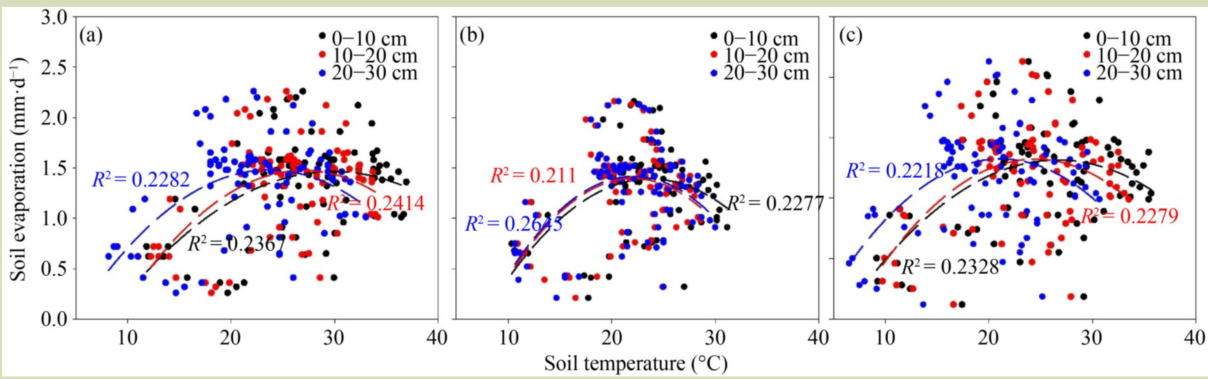

Fig. 9 Relationships between daily soil evaporation (SE) and soil temperature (ST) at different soil depths under three treatments of film mulching (FM) with drip irrigation (DI) (a), maize straw mulching (SM) with DI (b), and clear tillage (TL) with DI (c) during the study period.

found that the cumulative SE decreased with increasing sand-mulch thickness during the freeze–thaw period. Also, variations in soil physical parameters, hydraulic conductivity and energy input can also affect SE dynamics[21,55,56]. During the study period, differences in the above variables might exist between the treatments and these variables jointly affected SE dynamics of the young orchard. Consequently, the daily SE of the young orchard under FM and SM treatments showed similar seasonal variations.

4.2 SE characteristics and soil moisture variations under different treatments

Compared to the TL treatment, the daily SE of the young orchard under FM and SM treatments was more responsive to meteorological factors. Stepwise regression analysis revealed that the relationships between daily SE and the main controlling factors also differed between the treatments. Poulsen et al.[43] found that the spatial distribution of local SE in furrowed soil was strongly dependent on WS and its direction, whereas there was no significant relationship between daily SE of the young orchard and WS under TL treatment ($p > 0.05$). The SWC is an essential state variable that controls water and energy balance processes between the land surface and atmosphere[44,57]. Generally, the SE rate primarily changes with respect to SWC and its availability[40,58]. Although FM and SM treatments significantly improved SWC, especially in the 0–30 cm layer ($p < 0.05$), the SWC throughout the soil profile had little effect on the variation in daily SE in each treatment ($p > 0.05$). Zheng et al.[29] found that the SWCs at various sampling points under SM were consistently higher than those under plastic mulch in an apple-soybean intercropping system. The oven-drying method is widely used due to its advantages of relatively low cost and easy and accurate results, but this technique is labor and time intensive and cannot measure SWC variations continuously[59]. In our study, SWC data were obtained at about 10-d intervals, and insufficient data were available to identify the relationships between daily SE and SWC in different soil layers. Our next planned research is to investigate SWC characteristics throughout the soil profile and the interactions between SWC dynamics and variations in the daily SE of a young orchard between treatments.

Although SE can enhance the transpiration process by creating a favorable microclimate in some cases[60,61], SE is still commonly considered an unproductive component[18,19]. SE is an important process for regional water balance and has a significant influence on agricultural management, soil water availability and groundwater recharge[40,62,63]. The cultivation of apple orchards continues to expand on the Loess Plateau, and the unproductive SE flux in young orchards and its effects on local water balances should be seriously considered. Thus, appropriate agricultural management practices should be implemented to divert SE to plant production and improve the water use efficiency of apple orchards[24,64]. Compared to the TL treatment, the FM and SM treatments clearly reduced the total SE losses of the young orchard, and there were no significant differences in TH and TD of the young orchard between FM and SM treatments ($p > 0.05$). SWC is important in hydrological and biological processes such as plant growth and land–atmosphere interactions[65,66]. The daily SWC was consistently higher under SM treatment than under FM and TL treatments. Considering the better SWC conditions under SM treatment, SM was considered a more appropriate mulching practice for reducing SE losses and improving the SWC status of young orchards with DI in arid areas. In the future, the estimation of SE and SWC can be combined with transpiration and water use efficiency measurements, which can further improve understanding of the effects of the combination of DI and mulching practices on the water use characteristics of young orchards in arid or similar climatic regions.

5 Conclusions

This study investigated the effects of the combination of DI and mulching practices on SE characteristics in a young apple orchard in an arid area. The key findings of this study were as follows.

(1) FM and SM practices significantly reduced SE losses in young orchards with DI. The daily mean SE of the young orchard under FM, SM, and TL treatments was about 1.3 ± 0.5, 1.3 ± 0.4, and 1.7 ± 0.4 mm·d^{-1}, respectively, whereas there was no significant difference in daily SE of the young orchard between FM and SM treatments.

(2) The daily SE of this young apple orchard under FM and SM treatments was more responsive to meteorological factors than those under TL treatment. The daily SWC throughout the soil profile under FM, SM, and TL treatments ranged from 14.3 to 15.2, 14.9 to 15.6, and 13.9 to 15.1 cm^3·cm^{-3}, respectively, whereas no significant relationships occurred between daily SE and SWC in the soil layers in each treatment.

Our results highlight the significant differences in SE and SWC between the treatments applied. As a result, SM practices should be carefully considered when selecting appropriate mulching practices in young orchards with DI in this region.

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Compliance with ethics guidelines

Xinyu Wang, Haijing Wang, Xiao Li, and Di Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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