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Mulching and irrigation strategies for climate resilient apple cultivation in high-density orchards

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Rising temperatures due to climate change pose challenges for temperate crops hence, understanding soil hydrothermal dynamics is critical for optimizing crop yield. This study hypothesizes that optimum soil conditions, and effective moisture conservation are necessary for high-density apple orchards with M9 dwarfing rootstocks to maximize productivity. The present research investigates the impact of two irrigation levels (100% and 85% crop evapotranspiration (ETc)) and three mulching treatments (plastic mulch, dried grass mulch, and no mulch) on high-density apple plantations within a sub-humid agro-climatic zone in Himachal Pradesh, India, evaluated over two years. The study examines how different mulches affect soil nutrient dynamics and explores the interaction between mulch types and varying irrigation levels (full and deficit) on soil fertility. Beyond soil fertility, the research also investigates the effects of mulching on soil temperature, where it was observed that grass mulch significantly reduced maximum soil temperatures by an average of 2.2 ˚C, increased minimum soil temperatures by 1.3 ˚C compared to no mulch, and improved moisture conservation. The combination of grass mulch and 100% ETc irrigation achieved the highest yield (80.8 and 83.3 Mg ha^{-1} in 2022 and 2023, respectively). However, the 85% ETc irrigation level achieved a higher water use efficiency (WUE), showing a 13.6% increase over 100% ETc in 2022 and a 12.7% increase in 2023. Deficit irrigation affected stomatal density, indicating its sensitivity to water availability. For optimal crop productivity in high-density apple orchards, using grass mulch with 100% ETc irrigation is recommended. Alternatively, 85% ETc irrigation can be used where water conservation is a priority without compromising yield and profit. These findings demonstrate that using grass mulch in combination with appropriate irrigation can improve climate resilience in high-density apple orchards by maintaining temperature stability, conserving moisture, and enhancing WUE under water-scarce conditions.

Keywords Apple yield, Mulch, Soil hydrothermal properties, Climate resilient horticulture, Water use efficiency

Climate change and water scarcity are acknowledged as significant threats to sustainable development, particularly in developing countries[1]. Both water scarcity and excess pose significant challenges to crop productivity, and these stresses are expected to become more severe with increasing climate variability[2]. As global concerns regarding water and food security continue to rise, it is necessary to explore effective strategies that promote efficient resource utilization such as improved irrigation, mulching, varietal selection, and nutrient management[3]. Among these, the adoption of mulching has proven effective in mitigating water stress and optimizing soil health[4]. Research consistently shows that soil mulch measures can significantly improve soil physiochemical properties and water conditions, leading to enhanced plant growth and increased crop yields[5–7]. By covering the soil surface with organic or synthetic materials, mulching offers numerous benefits beyond moisture retention, such as weed suppression, temperature moderation, and erosion control in various agricultural systems[8,9]. Specifically, mulches help minimize soil evaporation, preserve moisture levels, improve soil fertility, and mitigate temperature extremes[10]. Building on this foundation, this study specifically addresses the unique challenges that temperate crops face in the mid-hills, where climate variability demands sustainable practices. While plastic mulch has shown benefits for tropical crops by increasing soil temperature and enhancing microbial activity, temperate crops may respond differently, often favoring lower soil temperatures[11,12]. This study investigates

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these dynamics by comparing organic and plastic mulches, focusing on their effects on the soil's hydrothermal properties and how they interact within the surface soil to influence apple orchard productivity.

In addition to mulching, optimizing irrigation levels is another crucial aspect of water management in apple orchards[13]. Proper irrigation, balancing water supply to meet crop needs while considering the impacts of excessive or insufficient water on soil moisture levels and tree health, is crucial for sustaining high agricultural productivity and ensuring sustainable water management[14]. Striking the right balance between water requirements and conservation is the key to enhancing water use efficiency, ensuring optimal tree health, and maintaining sustainable orchard practices. There is a need to understand physiological parameters of the tree and water use efficiencies to optimize irrigation and conserve water resources. In this study, we have examined the effects of different mulch and irrigation levels on moisture distribution and temperature dynamics in apple orchards, considering both full irrigation and deficit irrigation approaches. By comprehending the complex relationship between mulching, irrigation doses, temperature, and moisture distribution in apple orchards, orchard managers can make informed decisions that not only optimize water utilization, conserve resources, and regulate temperature extremes but also have a direct impact on apple yield, fostering long-term sustainability.

Studies have explored the correlation between deficit irrigation and mulch effects on apple yield[15,16], where they have compared the effects of organic mulch versus plastic mulch, straw versus plastic film mulch, and the combination of mulching and deficit irrigation on the soil environment and apple productivity[15,17,18]. While existing studies offer valuable insights, our research uniquely examines high-density apple orchards in the mid-hills of Himachal Pradesh, characterized by a sub-humid agro-climatic zone. This focus is particularly significant, as sub-humid regions are vulnerable to fluctuating precipitation patterns, which directly affect orchard productivity and water resource management. This unique focus enhances the understanding of mulching and irrigation practices in a distinct geographical and environmental context, contributing new knowledge to the literature on orchard management in this climate-sensitive area. High-density plantations are necessary to maximize land use efficiency, increase crop yield per unit area, and meet the growing demand for food, especially in regions with limited arable land.

Our study hypothesizes that in high-density apple plantations with the shallow-rooted M9 dwarfing rootstock, close planting spacing intensifies competition for resources, making soil microclimate and fertility critical for optimal growth. This is particularly important as shallow roots are more vulnerable to fluctuations in surface temperature and moisture, which can severely affect plant health and productivity. Studies conducted in the lower hills of Uttarakhand have highlighted how extreme weather conditions, such as rising temperatures and uneven precipitation, threaten temperate crop production. These challenges have led to the suggestion of adopting low-chilling apple varieties or shifting to alternative crops like kiwi and pomegranate in regions affected by poor climatic conditions[19]. This study, conducted in Himachal Pradesh, addresses the challenges faced by high density temperate crop plantations in the mid-hills and increase the understanding of mulching and irrigation practices across such environmental settings. By focusing on this sub-humid mid-hill region, we compare and contrast the effects of mulching and irrigation strategies, thereby enriching existing knowledge and providing insights applicable to different agro-climatic zones. The mid-hill regions are important as they act as crucial buffer zones for temperate crops. However, climate change is increasingly reducing their suitability for sustaining such crops. Additionally, our study examines the distinct impacts of plastic mulch and grass mulch on soil nutrient dynamics and investigates the interaction between these mulch types and varying irrigation levels (full and deficit) on soil fertility, which has been less explored. These factors are directly linked to improvements in water use efficiency and yield stability in high density apple orchards.

Materials and methods

Location

The experimental site is situated at the experimental farm of the Department of Soil Science and Water Management, Dr. YS Parmar University of Horticulture and Forestry, Solan, Himachal Pradesh (HP), India (Fig. 1). It is located at 30º 51′24.43” N latitude and 77º 10′29.09” E longitude and has an elevation of 1,181 m above mean sea level. Initial soil physico-chemical characteristics of the experimental area are presented in Table 1.

Climate

The study area experimental farm, falls in the mid hills sub-humid agro-climatic zone of Himachal Pradesh (Zone-II). The area receives an annual rainfall of 1100 mm and about 75% of which, is received during the monsoon period (mid-June to mid-September). Winter rains are meager and received during the months of January and February. The meteorological data on weekly distribution of rainfall, evapotranspiration, temperature (maximum and minimum) and relative humidity recorded at the Meteorological Observatory of the Department of Environment Science, Dr. YS Parmar University of Horticulture and Forestry, Solan (HP) during the experimental period (March-September) for both the years are presented in Fig. 2. A total of 819.8 mm and 1724.0 mm rainfall was received during the experimental period in the year 2022 and 2023, respectively.

Experimental design

Five year old apple trees (Var. Red Velox, rootstock M9) under high density plantation (2.5 m x 1 m) (row direction- East to West), irrigated through a surface drip system was chosen for the study. Treatments comprised of two irrigation levels (100 and 85% ETc) and 3 mulch levels (plastic mulch, grass mulch and no mulch) (Table 2). The selection of mulching materials was based on their availability, cost-effectiveness, and widespread use in the local area, ensuring relevance to both small-scale and large-scale orchards. For plastic mulch, we used conventional black polyethylene mulch, with a thickness of 50 microns. For grass mulch, we harvested locally available weed grass before the flowering stage, to prevent weed germination from seeds, dried it and

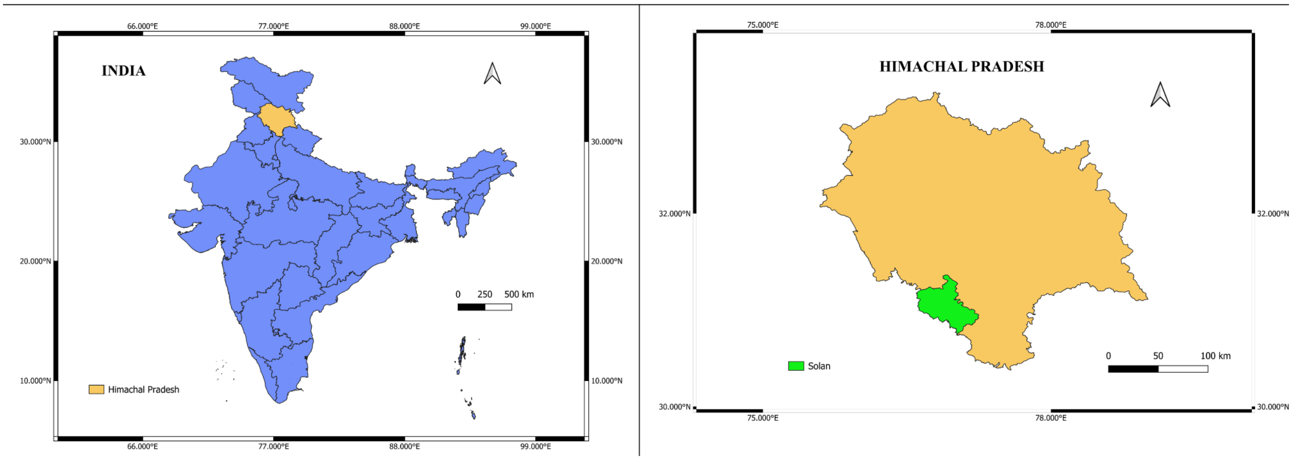

Fig. 1. Study area map showing the geographical location of Himachal Pradesh within India (left) and a detailed map of Himachal Pradesh highlighting the district of Solan (right), where the study was conducted. The map was generated using QGIS Desktop 3.34.4 (https://qgis.org).

Particulars	Values	
	0–15 cm	15–30 cm
Texture	Sandy clay loam	
Bulk density (Mg m^{-3})	1.28	1.29
Particle density (Mg m^{-3})	2.47	2.47
Pore space (%)	48.2	47.7
Water Holding Capacity (%)	48.6	44.3
Field capacity (%)	25.0	23.2
pH (w/v = 1/2.5)	6.8	6.30
EC (w/v = 1/2.5) (dS m^{-1})	0.2	0.16
Organic carbon (g kg^{-1})	1.5	1.24
Available N (kg ha^{-1})	286	267
Available P (kg ha^{-1})	88.2	81.7
Available K (kg ha^{-1})	298	281
DTPA Zn (mg kg^{-1})	1.1	0.80
DTPA Cu (mg kg^{-1})	2.4	1.90
DTPA Fe (mg kg^{-1})	74.2	68.4
DTPA Mn (mg kg^{-1})	10.3	8.10

Table 1. Physico-chemical characteristics of the experimental soil before the start of the experiment.

applied. Two layers of grass mulch were applied to ensure complete coverage, leaving no soil exposed. The experimental design followed was Factorial Randomized Block Design (FRBD). Every treatment was replicated four times with three trees in a plot. The treatments were compared against corresponding plots without mulch, which served as the control. In our study, we did not include a non-irrigated control, since the main purpose of the study was to exploit the possible mechanisms by which 85% ETc treatments over-performs 100% ETc in terms of improving WUE. 85% ETc was implemented as a mild deficit irrigation strategy, designed to reduce water usage without compromising growth performance[20]. The CROPWAT model was used to determine the irrigation requirement and irrigation was scheduled according to the effective rainfall obtained in the season so that crop evapotranspiration demands were met. The trees were supplied with a recommended dose of fertilizers (35:17.5:35 kg NPK ha^{-1}) through drip irrigation in 14 splits and all other management practices such as pruning, thinning, and weeding were practiced according to the package of practices recommended by the Department of Horticulture, Dr. YS Parmar University of Horticulture and Forestry, Solan (HP). An overview of the experimental plot is given in Fig. 3.

Sampling for hydrothermal properties

Moisture content and soil temperature were assessed during five critical growth stages, namely the Green tip/pink bud stage (March to April) (Stage 1), Flowering/fruit set stage (April to May) (Stage 2), Walnut stage (May) (Stage 3), Fruit development stage (June) (Stage 4), and pre-harvest fruit development stage (July) (Stage 5). Tree roots were partially excavated prior to the experiment to examine their distribution, revealing that the majority

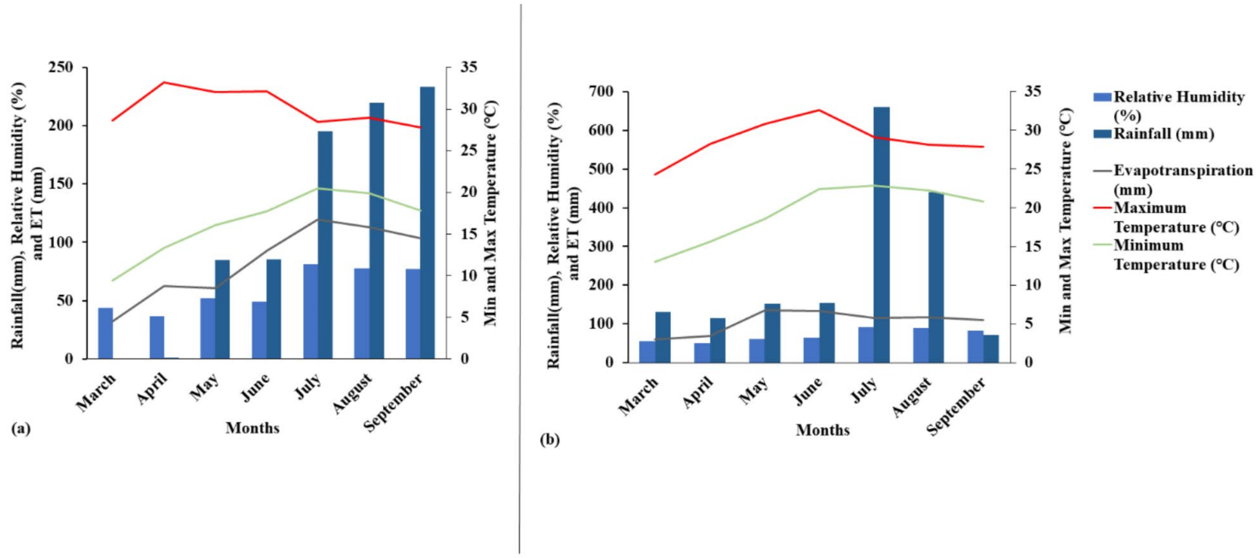

Fig. 2. Meteorological data during the experiment period (**a**) March – September, 2022 and (**b**) March – September, 2022.

Treatment name	Treatment details
M_1I_1	Plastic mulch and 85% ETc irrigation
M_1I_2	Plastic mulch and 100% ETc irrigation
M_2I_1	Grass mulch and 85% ETc irrigation
M_2I_2	Grass mulch and 100% ETc irrigation
M_3I_1	No mulch and 85% ETc irrigation
M_3I_2	No mulch and 100% ETc irrigation

Table 2. Details of different treatment combinations used in the experiment.

of roots were concentrated at a depth of 30 cm, for which a 30 cm scale was used to take readings (Fig. 4). Using a gravimetrically calibrated digital moisture meter (Lutron PMS-714), readings were taken throughout the crop growth period and stage-wise mean values were calculated at depths of 5, 10, and 30 cm along the row, near the root zone of the tree. Simultaneously, a digital soil thermometer was employed to measure minimum (at 7:00 h) and maximum soil temperature (at 14:00 h) values at the same three depths during each of the specified growth stages. The thermometer remained in the field throughout the study period.

Stomatal parameters

To assess stomatal density in treated plant leaves, Olympus microscope (CX41) aided with a real-time Nikon camera loaded with a micro-image projection system (MIPS) was used. Physiologically active leaves were collected, peeled, and affixed to slides. Slides were examined for the stomatal count and aperture[21]. Calculation of stomatal density was done by dividing the number of stomata per microscopic field by the area of the microscopic field (mm^2).

Crop yield

During the months of July and August, the apple harvest took place. During the harvest, the yield (total weight of the fruits) produced by each individual apple tree was carefully observed and recorded. To provide a standardized measure of yield, the individual tree yields were then converted to mega grams per hectare.

Water use efficiency

The following equation was used to calculate water use efficiency and the results were expressed in Mg ha^{-1} cm^{-1}.

$$\text{WUE} = \frac{\text{Fruit yield (Mg/ha)}}{\text{Total amount of water applied through irrigation (cm)}}$$

Fig. 3. Overview of the experimental area (**a**) at the initiation of trial and (**b**) at harvest.

Soil nutrient content

Soil samples were collected from the upper soil layer (0–15 cm) to assess the nutrient content. The sampling was conducted systematically across all experimental plots to ensure representative data[22]. Standard procedures were followed for soil sample collection, preparation, and analysis. The soil samples were air-dried, ground, and sieved through a 2 mm mesh to obtain a uniform sample. Nitrogen (N) content was determined using the Kjeldahl method[23], phosphorus (P) content was measured using the Olsen extraction method[24], and potassium (K) content was assessed using a flame photometer[25].

Fig. 4. Distribution of apple tree roots in the soil profile.

Economic feasibility analysis

Benefit cost ratio indicates the amount of money earned by investing a given unit amount of the money. The cost of the apple was kept at 80 INR (approximately 0.95 USD) per kg. Fixed cost accounted for 8,84,149 INR (approximately 10,474.58 USD) per ha. Variable cost changed with respect to the treatments. The net return was calculated by subtracting the total production cost per hectare (comprising both fixed and variable costs) from the gross value of production. The benefit–cost ratio (BCR) was determined by dividing the gross value of production by the total production cost per hectare[26].

Statistical analysis

The experiment was conducted using a Factorial Randomized Block Design (FRBD) to systematically analyze the interaction effects of two factors: mulching and irrigation levels, accounting the variability among blocks[27]. The mulching factor consisted of three levels (plastic mulch, dried grass mulch, and no mulch), while the irrigation factor had two levels (100% ETc and 85% ETc). The FRBD was selected due to its suitability for experiments involving multiple factors and interactions. This design allowed us to systematically evaluate the interaction effects of mulching and irrigation, ensuring comprehensive and reliable results. Further Duncan's Multiple Range Test (DMRT) was used for post-hoc comparisons to identify significant differences between treatment means[28].

Results

Soil moisture

Soil moisture data from various depths exhibited a declining trend with depth across all treatments, although the extent of variation differed significantly. Figures 5 and 6 illustrate variations in soil moisture content with respect to depth and season. In 2022, soil moisture contents were higher under plastic mulch ranging from 14.3 to 16.7% (at 30 cm and 5 cm, respectively), during the early growth stages (stage 1, green tip stage). Subsequently, Grass mulch exhibited increased moisture content during stage 2 (16.8%) till stage 5 (19.0%) at 5 cm depth. In the year 2023, characterized by continuous rainfall from the initial growth stages (green tip/pink bud stage) to harvesting, soil moisture content remained consistently higher under grass mulch, (ranging from 18.1 to 23.0%) throughout the season.

Soil temperature

Effect of different levels of mulch and irrigation doses on soil thermal properties are presented in Figs. 7 and 8. The minimum temperature data for 2022 indicate that soil temperatures were highest under M_1I_2 during the green tip, flowering, walnut, fruit development stages and pre-harvest stages (18.0, 24.2, 24.8, 27.5 and 27.0 °C). A similar effect was also observed in 2023, with a clear cut difference between all the three mulches where, M_1I_2 recorded highest values for minimum soil temperature (18.5, 22.2, 24.0, 26.0 and 27.6 °C). In both years, M_2I_1 and M_2I_2 exhibited minimum temperature values that were higher than those observed under no mulch but lower than the treatments implemented with plastic mulch. No mulch recorded lowest value for minimum temperature throughout the study period. Minimum soil temperature increased with depth, irrespective of the mulch conditions.

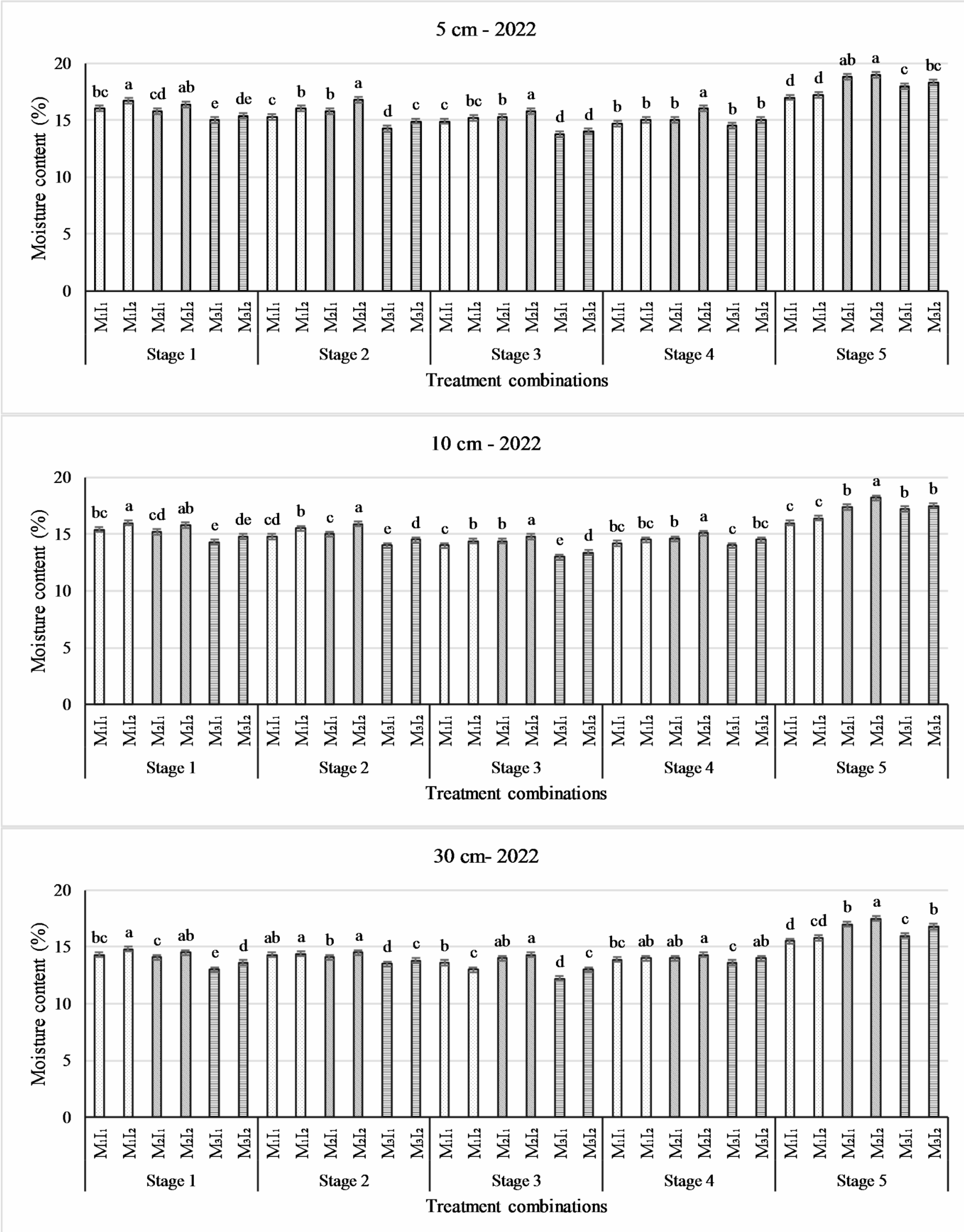

Fig. 5. Vertical distribution of soil moisture (% w/w) (2022) at different growth stages (mean values are given) (Stage 1—green tip/pink bud, 2—flowering / fruit set, 3—walnut, 4—fruit development, and 5—pre-harvest fruit development).

Maximum temperature data showed a different trend. In 2022, M_1I_1 showed highest soil temperature in all growth stages (31.4, 40.1, 35.0, 31.8 and 29.1 °C). The treatment M_2I_2 recorded lowest maximum temperature throughout the growing season (27.5, 34.3, 29.1, 25.1 and 24.7 °C). Whereas, treatments without mulch recorded values that fell between the temperatures observed under plastic and grass mulches. The same trend was observed in 2023, with temperature values ranging from 30.1 to 38.9 °C under M_1I_1 and 25.8 to 32.7 °C under M_2I_2. No

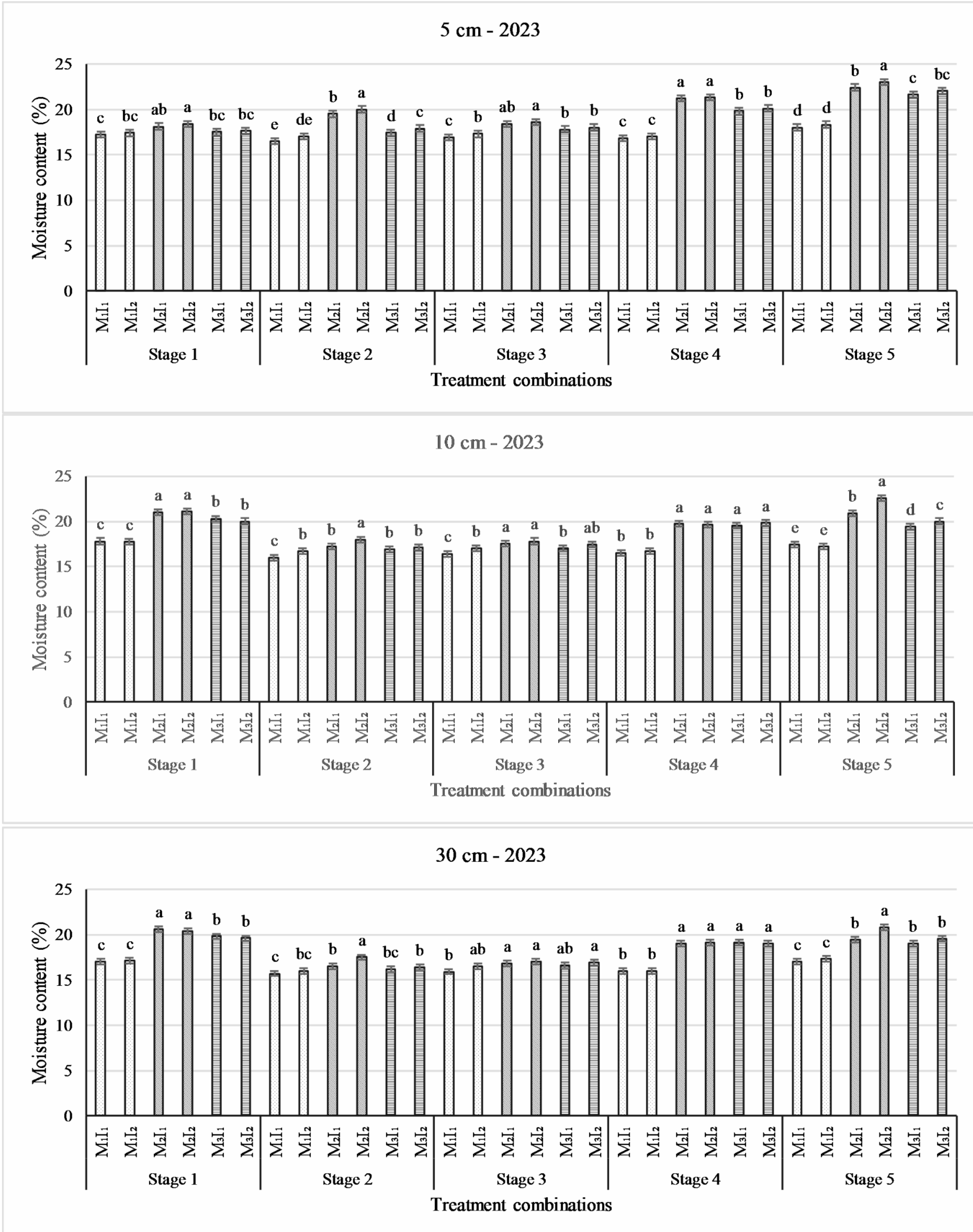

Fig. 6. Vertical distribution of soil moisture (% w/w) (2023) at different growth stages (mean values are given) (Stage 1—green tip/pink bud, 2—flowering / fruit set, 3—walnut, 4—fruit development, and 5—pre-harvest fruit development).

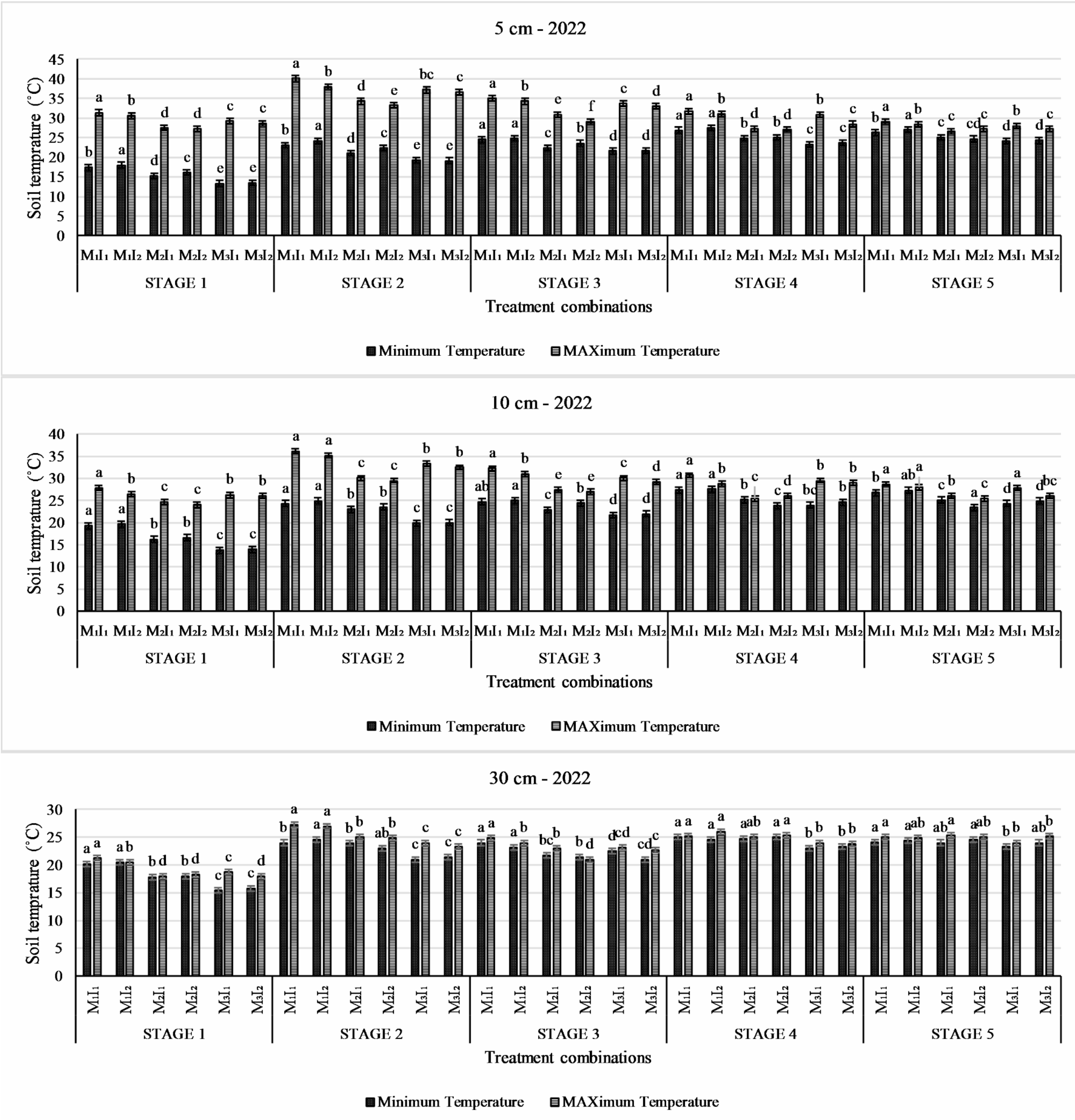

Fig. 7. Minimum and maximum soil temperature (℃) at different soil depths, 2022. Different growth stages (mean values are given) (Stage 1—green tip/pink bud, 2—flowering / fruit set, 3—walnut, 4—fruit development, and 5—pre-harvest fruit development).

mulch recorded values in between plastic and no mulch (M_3I_1: 27.8 to 35.0 °C and M_3I_2: 27 to 34.2 °C). Lower soil layers showed lesser temperature variations.

Apple yield

In both years, grass mulch (M_2: 79.3 Mg ha^{-1} in 2022, 80.1 Mg ha^{-1} in 2023) consistently resulted in the significantly highest fruit yields, followed by plastic mulch (M_1: 75.6 Mg ha^{-1} in 2022, 71.5 Mg ha^{-1} in 2023), with the lowest yields observed in no mulch (M_3: 70.7 Mg ha^{-1}in 2022, 67.3 Mg ha^{-1} in 2023) indicating that the type of mulch significantly affects fruit yield (Table 3).

Fruit yield was significantly higher under the 100% irrigation level (I_2: 76.5 Mg ha^{-1} in 2022, 75.3 Mg ha^{-1} in 2023) compared to the 85% irrigation level (I_1: 73.9 Mg ha^{-1} in 2022, 70.7 Mg ha^{-1} in 2023) in both years. No significant interaction effects were observed between mulch and irrigation treatments in either year.

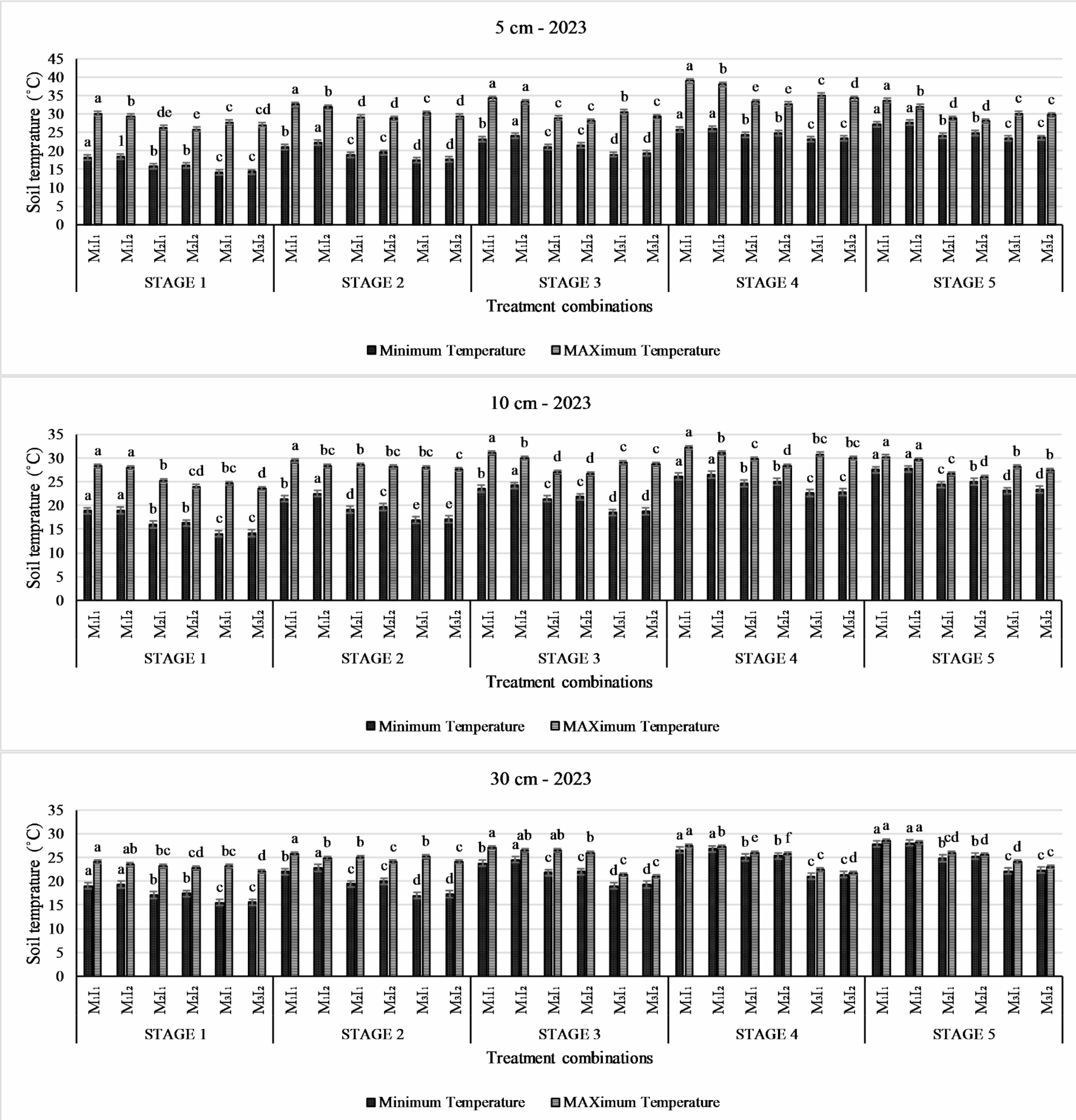

Fig. 8. Minimum and maximum soil temperature (℃) at different soil depths, 2023. Different growth stages (mean values are given) (Stage 1 – green tip/pink bud, 2 – flowering / fruit set, 3 – walnut, 4 – fruit development, and 5 – pre-harvest fruit development).

Water use efficiencies

In both years, grass mulch (M_2: 5.0 Mg ha^{-1} cm^{-1} in 2022, 12.7 Mg ha^{-1} cm^{-1} in 2023) consistently resulted in the significantly highest WUE, followed by plastic mulch (M_1: 4.8 Mg ha^{-1} cm^{-1} in 2022, 11.6 Mg ha^{-1} cm^{-1}in 2023), with the lowest WUE observed in no mulch (M_3: 4.5 Mg ha^{-1} cm^{-1} in 2022, 10.9 Mg ha^{-1} cm^{-1} in 2023) (Table 4). In both years, WUE was higher under the 85% irrigation level (I1: 5.0 Mg ha^{-1} cm^{-1} in 2022, 12.4 Mg ha^{-1} cm^{-1} in 2023) compared to the 100% irrigation level (I2: 4.4 Mg ha^{-1} cm^{-1} in 2022, 11.0 Mg ha^{-1} cm^{-1} in 2023). The results indicate that both mulches and irrigation doses affects WUE in high density apple. No significant interaction effects were observed between mulch and irrigation treatments in either year.

Stomatal parameters

Data regarding stomatal density and aperture size are provided in the Tables 5 and 6. Stomata observed under microscope at different magnifications are displayed in Fig. 9. In both years, the M_3 had the highest stomatal

Fruit yield (Mg ha^{-1})	2022			2023		
	I_1	I_2	Mean	I_1	I_2	Mean
M_1	75.2	76.0	75.6	69.7	73.4	71.5
M_2	77.9	80.8	79.3	76.9	83.3	80.1
M_3	68.8	72.6	70.7	65.5	69.1	67.3
Mean	73.9	76.5	75.2	70.7	75.3	73.0
	SE	CD	SE	CD		
Factor (M)	0.81	1.73	0.84	1.80		
Factor (I)	0.66	1.42	0.69	1.47		
Interaction (M × I)	1.15	NS	1.19	NS		

Table 3. Effect of different mulches and irrigation doses on fruit yield (level of significance: 5%).

WUE (Mg ha^{-1} cm^{-1})	2022			2023		
	I_1	I_2	Mean	I_1	I_2	Mean
M_1	5.1	4.4	4.8	12.2	10.9	11.6
M_2	5.3	4.7	5.0	13.4	11.9	12.7
M_3	4.7	4.2	4.5	11.5	10.2	10.9
Mean	5.0	4.4	4.7	12.4	11.0	11.7
	SE	CD	SE	CD		
Factor (M)	0.06	0.12	0.12	0.25		
Factor (I)	0.05	0.10	0.09	0.20		
Interaction (M × I)	0.08	NS	0.16	NS		

Table 4. Effect of different mulches and irrigation doses on water use efficiencies (level of significance: 5%).

Stomatal density (mm^{-2})	2022			2023		
	I_1	I_2	Mean	I_1	I_2	Mean
M_1	386	383	385	375	372	373
M_2	387	381	384	373	370	372
M_3	390	384	387	378	374	376
Mean	388	383	385	375	372	374
	SE	CD	SE	CD		
Factor (M)	3.49	NS	4.46	NS		
Factor (I)	2.85	NS	3.64	NS		
Interaction (M × I)	4.93	NS	6.30	NS		

Table 5. Effect of different mulches and irrigation doses on stomatal density. (level of significance: 5%)

Stomatal aperture (µm)	2022			2023		
	I_1	I_2	Mean	I_1	I_2	Mean
M_1	19.1	19.7	19.4	20.0	20.1	20.1
M_2	20.7	22.2	21.5	21.1	22.0	21.5
M_3	18.0	19.7	18.9	19.9	20.9	20.4
Mean	19.3	20.5	19.9	20.3	21.0	20.7
	SE	CD	SE	CD		
Factor (M)	0.18	0.37	0.16	0.34		
Factor (I)	0.14	0.31	0.13	0.28		
Interaction (M × I)	0.25	0.53	0.23	0.48		

Table 6. Effect of different mulches and irrigation doses on stomatal aperture. (level of significance: 5%)

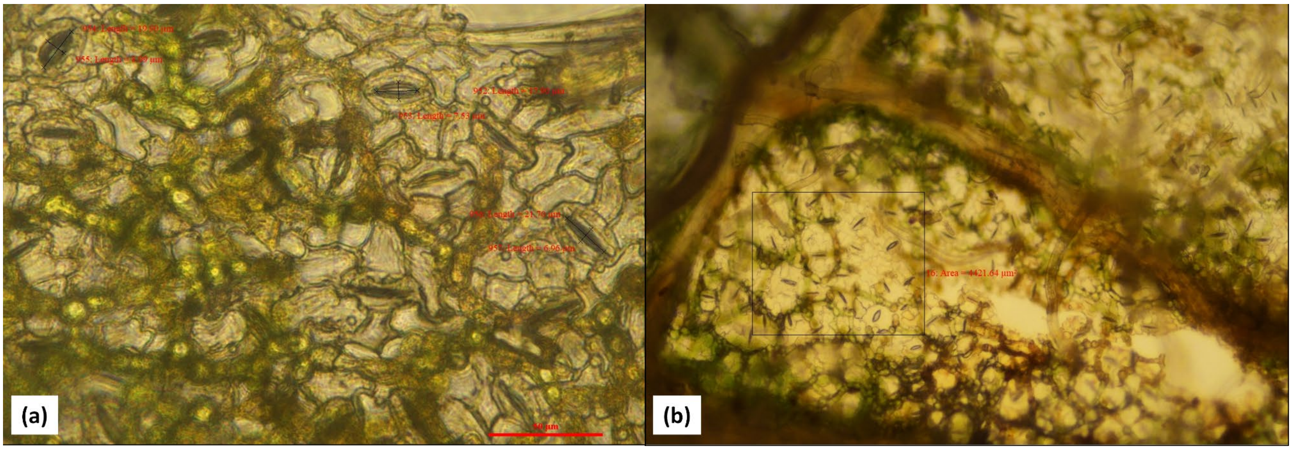

Fig. 9. Stomata observed under microscope at (**a**) 40x and (**b**) 10x magnification.

	N			P			K		
	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean
M_1	316	313	315	100	100	100	361	358	360
M_2	321	320	321	102	102	102	366	363	365
M_3	308	306	307	99	99	99	357	351	354
Mean	315	313	314	100	100	100	361	357	359
	SE	CD	SE	CD	SE	CD			
Factor (M)	2.53	5.38	0.74	1.58	2.30	4.90			
Factor (I)	2.06	NS	0.61	NS	1.88	NS			
Interaction (M × I)	3.57	NS	1.05	NS	3.25	NS			

Table 7. Effect of different mulches and irrigation doses on soil nutrient content. (level of significance: 5%)

density (387 mm^{-2} in 2022 and 376 mm^{-2} in 2023), followed by M_1 (385 mm^{-2} in 2022 and 373 mm^{-2} in 2023) and M_2 (384 mm^{-2} in 2022 and 372 mm^{-2} in 2023), although these differences were not statistically significant. Deficit irrigation (I_1) generally resulted in higher stomatal density (388 mm^{-2} in 2022 and 375 mm^{-2} in 2023) compared to full irrigation (I_2) (383 mm^{-2} in 2022 and 372 mm^{-2} in 2023), but these differences were also not significant. The interaction between mulching and irrigation levels did not significantly affect stomatal density. The overall mean stomatal density decreased from 2022 (385 mm^{-2} to 2023 (374 mm^{-2}), likely due to unprecedented rainfall experienced in the second year, indicating potential year-to-year variability influenced by environmental factors.

In both years, M_2 had the highest stomatal aperture (21.5 µm for both 2022 and 2023), followed by no mulch M_3 (18.9 µm in 2022 and 20.4 µm in 2023) and M_1 (19.4 µm in 2022 and 20.1 µm in 2023), with statistically significant differences among the mulch treatments. Full irrigation (I_2) generally resulted in higher stomatal apertures (20.5 µm in 2022 and 21.0 µm in 2023) compared to deficit irrigation (I_1) (19.3 µm in 2022 and 20.3 µm in 2023), with these differences also being statistically significant. The interaction between mulching and irrigation levels significantly affected stomatal aperture with M2I2, resulting in significantly large aperture (22.2 and 22.0 µm in the year 2022 and 2023, respectively).

Soil nutrient content after the completion of trial (15 cm)

The nutrient content of nitrogen, phosphorus, and potassium in the soil showed significant variation among different mulch treatments, while irrigation levels and their interactions with mulch treatments did not have significant effects (Table 7). Treatment M_2 consistently resulted in the highest nutrient levels, with N content at 321 kg ha^{-1}, P content at 102 kg ha^{-1}, and K content at 365 kg/ha, which was followed by M_1, with N content at 315 kg/ha, P content at 100 kg ha^{-1}, and K content at 360 kg ha^{-1}. Treatments M_3 recorded the lowest nutrient levels, with N content at 307 kg ha^{-1}, P content at 354 kg ha^{-1}, and K content at 354 kg ha^{-1}. This trend suggests that grass mulch is most effective in enhancing soil nutrient content, followed by plastic mulch, with no mulch treatments being the least effective.

Treatment details		NR (INR in lakhs)		BCR	
		2022	2023	2022	2023
M_1I_1	Plastic mulch, 85% ETc	50.47	45.82	6.22	5.60
M_1I_2	Plastic mulch, 100% ETc	51.13	48.34	6.29	5.85
M_2I_1	Grass mulch, 85% ETc	53.11	51.07	6.79	6.12
M_2I_2	Grass mulch, 100% ETc	55.48	53.70	7.05	6.39
M_3I_1	No mulch, 85% ETc	46.18	42.70	6.20	5.41
M_3I_2	No mulch, 100% ETc	49.21	45.23	6.55	5.68

Table 8. Effect of fertigation levels and mulches on economics of apple production.

Economic feasibility and profitability

Details regarding the benefit-cost ratio (BCR) and net returns (NR) are presented in Table 8. In 2022, the highest BCR was observed under treatment M_2I_2 (7.05), followed by M_2I_1 (6.79). Same trend was observed in 2023, with a lower BCR for treatment M_2I_2 (6.39) and M_2I_1 (6.12).

Discussion

The data suggest that the application of mulch aids in reducing irrigation requirements for high-density apple plantations by conserving soil water. Minimizing evaporation and increasing rainfall infiltration are two keys to soil moisture conservation[11,29]. While plastic mulch conserved water primarily by reducing evaporation, grass mulch not only reduced evaporation but also maintained moisture through enhanced rainfall infiltration, slower surface seepage, and minimized runoff loss. The shift in moisture content from the walnut to fruit development stage was attributed to rainfall received during the later growth stages. Grass mulch likely facilitated greater infiltration of rainwater compared to plastic mulch. Similar results were reported by Rahma et al. (2017), where straw mulch enhanced rainfall infiltration by increasing surface roughness and tortuosity of flow paths, reducing flow velocities into the soil[30]. The layered structure of grass mulch also played a role in minimizing moisture loss through evaporation. In all cases higher irrigation level (I_1 = 100% ETc) resulted in higher moisture content. Decrease in moisture content with increasing depth can be attributed to the characteristic of drip irrigation, wherein the slow and intermittent supply of water tends to confine moisture predominantly to the upper soil layers.

Black plastic mulch has the capability to absorb a significant amount of radiation during the daytime, contributing to an increase in soil temperature[31]. Additionally, it acts as an insulator, preventing the rapid loss of temperature during the night[32]. This insulation effect leads to higher minimum temperatures in the soil. Soil under no mulch being directly in contact with the air showed temperature fluctuations according to the air temperature. The reduction of soil temperature under grass mulch could be attributed to the interactive effect between the high solar reflectance and low thermal conductivity resulting from the organic mulching layer[33,34]. The application of straw mulch reduced daytime soil temperature by an average of 1.9 °C in the 0–15 cm layer of soil[35]. Similarly, we observed that grass mulch significantly lowered maximum soil temperatures by 2.2 °C, with fluctuations ranging from 1.7 to 2.6 °C over two years, compared to no mulch in the upper soil layers. The layered structure of grass mulch along with its air pockets, provided an insulating effect that regulated extreme temperature fluctuations. Consequently, grass mulch effectively mitigates soil temperature fluctuations during the entire growing season, providing favorable conditions for both above-ground growth and root development of plants.

Plots under 100% ETc irrigation exhibited reduced maximum and elevated minimum soil temperatures. Full irrigation, characterized by its higher soil moisture content, facilitates efficient heat dissipation due to water's superior heat conductivity. Moist soil allows water to absorb and store more heat energy per unit mass, helping to prevent excessive temperature rise while maintaining a cooler soil environment. The increased minimum soil temperatures observed in plots under 100% ETc irrigation can be attributed to higher soil moisture, enhancing thermal inertia and reducing nocturnal heat loss, thereby sustaining elevated night-time temperatures[36,37]. A 0.5 °C rise in mean surface temperature across Himalayan districts were reported from the year 2000 to 2014, linked to global warming, which caused apple cultivation to shift to higher altitudes[38]. Addressing this issue, organic grass mulch has proven effective in reducing maximum soil temperature compared to plastic or no mulch conditions in our studies.

Soil moisture conservation and water use efficiency was higher in soil under plastic mulch during initial growth stages, but rainfall infiltration improved the moisture content under grass mulch in later growth stages. Grass mulch added organic matter and increased the fertility of the soil[39]. It was reported that grass mulches not only improve soil structure but also help in the slow release of nutrients and suppress extreme fluctuation of soil temperature[40]. As major factors affecting yield are nutrients and moisture, grass mulch clearly improved the yield of the crop. Reduction of yield and increase in WUE under deficit irrigation is in line with the findings of Li et al., (2022)[41]. The lack of significant interaction effects between mulch and irrigation treatments indicates that these factors influence fruit yield and WUE independently. This suggests that orchard managers have the flexibility to optimize either mulching or irrigation practices based on specific orchard needs, environmental conditions, or resource availability, without the need to account for their combined effects in decision-making.

Our study revealed that, grass mulch consistently achieved the highest water use efficiency (WUE) and significantly improved soil moisture conservation, particularly during later growth stages, by facilitating greater rainfall infiltration compared to plastic mulch. Deficit irrigation (85% ETc) further enhanced WUE, demonstrating that reduced irrigation levels can improve water use efficiency without substantially compromising yield. Previous research has established that stomatal density and size can vary due to genetic factors and environmental conditions[42]. Statistically, deficit irrigation (85% ETc) did not affected stomatal density when no mulch was applied indicating that, a stressed condition was not generated under the mulch. This implies, 25% reduction of irrigation did not affected stomatal morphology when the plants were under either plastic or grass mulch. Water use efficiency is a determining factor in the productivity of plant species and relates to the stomatal behaviour and density under limited water relations[43]. Studies have shown a significant positive correlation between stomatal density and water use efficiency (WUE), and a negative correlation between stomatal aperture and WUE[44]. Negative correlations between stomatal density and size were reported by Franks et al. (2009), aligning with our observations[45]. In this study, the 85% ETc irrigation level, which increased stomatal density, also improved WUE. However, it is important to note that the highest stomatal density did not correspond to the highest WUE. This suggests that while higher stomatal density can enhance WUE, other factors, such as more water availability under grass mulch, also play a crucial role. These results underscore the complex interplay between mulching, irrigation, stomatal characteristics, and WUE, providing valuable insights for optimizing orchard management practices.

Data after the completion of the experiment indicate that mulch type significantly influences soil nutrient content (NPK). Grass mulch consistently resulted in higher levels of these nutrients compared to plastic mulch and no mulch treatments suggesting that grass mulch has superior nutrient-releasing properties, which can enhance soil fertility. The lack of significant effects from irrigation levels and their interaction with mulch types indicates that the benefits of grass mulch in improving soil nutrient content are robust across different irrigation regimes. The ability of grass mulch to maintain higher nutrient levels could be attributed to organic matter addition and increased N and P cycling in soil owing to higher enzyme activity of urease and acid phosphatases, which gradually releases nutrients into the soil, implying higher supply and availability, as evidenced by our data[46]. These factors result in higher annual N mineralization rates in mulched plots than in non-mulched plots, implying greater N availability over time[47].The decomposition of grass mulch and the role of organic matter contribute significantly to increased nutrient content in the upper layers of soil, enhancing soil fertility and promoting better plant growth. Thus, incorporating grass mulch could be a sustainable practice to improve soil fertility and crop productivity, especially in temperate horticultural systems.

The results on economic feasibility analysis revealed that, highest net returns and BCR were consistently observed under the application of M_2I_2, indicating its potential to enhance farmers' income. Treatment M_2I_1 also demonstrated a high NR and BCR, which supports our findings that, 85% irrigation with grass mulch can be a viable strategy in water stressed areas without significant economic loss. The reduction in BCR and NR observed during the second year can be attributed to a decrease in yield caused by unprecedented rainfall and subsequent fruit drop.

Future research should extend this study over multiple seasons to assess the sustained impact of mulching and irrigation practices on orchard productivity and soil quality in temperate regions, while also considering other environmental factors, such as greenhouse gas emissions, that were not explored in this study. For instance, Cuello et al. (2015) reported that plastic film mulching significantly increased methane (CH_4) and nitrous oxide (N_2O) emissions, along with an overall increase in global warming potential in maize[48]. Our study contributes to this body of knowledge by demonstrating the advantages of grass mulch, which not only enhances soil fertility and stabilizes soil temperature but also improves water use efficiency and yield in high-density apple orchards. The findings suggest that grass mulch is a more sustainable and environmentally friendly option, providing a promising strategy for managing the challenges posed by climate change and promoting the resilience of temperate orchards in the mid-hills.

Conclusion

The application of grass mulch along with 100% ETc irrigation optimizes the performance of high-density apple orchards in the mid-hills with respect to yield. Grass mulch improves soil fertility by enhancing soil nutrient status through organic matter addition and gradual nutrient release from decomposition, as well as stabilizes soil temperature, resulting in significantly higher yields. The use of 85% ETc irrigation with grass mulching resulted in higher water use efficiency compared to other treatments, suggesting a potential trade-off between maximizing yield and adopting a more sustainable water conservation approach. High net returns and benefit cost ratio were also observed while using grass mulch. The practices are scalable across different climates and apple varieties, by using locally available dried grass with potential applications in both temperate and semi-arid regions. To support farmers, we recommend prioritizing grass mulching combined with irrigation practices based on the resource availability, in order to improve water use efficiency and offer long-term benefits for soil health and yield sustainability. Our study highlights the substantial yield increase and economic feasibility of grass mulch combined with 85% ETc irrigation, making it as a sustainable, cost-effective strategy for climate-resilient horticulture in high-density apple orchards.

Data availability

Data will be made available on request upon request to the corresponding author.

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Author contributions
SA and JCS conceptualized and designed the experiment, performed data analysis, and interpreted the findings. SA conducted the experiment, data analysis, and drafted the manuscript, while SVS provided support for data visualization and statistical analysis. JCS and NS critically reviewed and edited the manuscript. KumarS contributed his expertise to the microscopic analysis of apple leaves. RR, FL, KapilS, and AA contributed by assisting with the field experiments and drafting the manuscript.

Declarations

Competing interests
The authors declare no competing interests..

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