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ORIGINAL ARTICLE

Impact of Irrigation Treatments on Weed Flora and Seed Bank in Apple Orchards

Unal Asav[1]

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Abstract
Apple producers work to minimize the negative impacts of various biotic and abiotic factors on production, which can vary according to the specific conditions of each production area. In recent years, limited water availability due to global warming has necessitated alternative approaches to weed control, which is a common challenge in apple production. One of these may be the use of different irrigation systems to manage weed growth. This study aimed to determine the effects of three distinct irrigation systems on weed flora and the soil seed bank, assessing their potential for use in weed management. The experiment was conducted from 2021 to 2024 in an apple orchard with an 'Early Red One' cultivar grafted onto M9 rootstock. Over the years, there was a partial decrease in both the number and density of weeds in the furrow-irrigated and control plots. However, this decrease was more pronounced in plots with surface and subsurface drip irrigation. The control plots presented the greatest increase in the soil seed bank, followed by furrow irrigation, surface drip irrigation, and, with the smallest increase, subsurface drip irrigation. Compared with other irrigation systems, subsurface drip irrigation provides producers with advantages in managing weed flora while contributing to a slower rate of increase in the weed seed bank. These findings suggest that subsurface drip irrigation may offer a promising strategy for integrated weed management in apple orchards under conditions of water scarcity.

Keywords Irrigation system · Weed biodiversity · Weed seed bank · Surface drip irrigation · Subsurface drip irrigation · Furrow irrigation

Introduction

Global warming constitutes a phenomenon that transforms all agroecosystems, manifesting through droughts, heat waves, and dust storms (Zittis et al. 2022). Among these climatic events, drought emerges as potentially the most impactful, given its prolonged effects spanning several years. In the face of drought stress, every droplet of water, regardless of its source, holds immense value for plants. While the water demand of crop is lower than that of weed species, their response to water scarcity is more pronounced (Singh et al. 2022). This heightened sensitivity stems from the greater plasticity of weeds, which is attributed to certain mechanisms enabling them to adapt more readily to environmental changes (Amare 2016; Chongtham et al. 2019). Consequently, a pivotal inquiry arises for scientists: In the presence of irrigation resources, how can we enhance water use efficiency in support of crop cultivation?

Weeds engage in direct competition with crops and orchards, vying for access to finite resources such as nutrients, water, and sunlight. Their presence poses a threat to the quality and quantity of yields (Jordan and Russell 1981), as they serve as hosts for pests and diseases (Altieri 1999; Powell et al. 1984). Despite being unintentional in numerous cultivation fields, weeds are recognized as integral components of agroecosystems, contributing significantly to biodiversity (Wyss 1996). The management of weed flora in perennial fruit fields is a more intricate task than it is in nonagricultural settings owing to various abiotic factors, including tillage, irrigation, fertilization, and weather conditions, all of which are incorporated into this intricate equation (Hammermeister 2016). Each of these factors can swiftly alter the composition of weed flora, yet weeds exhibit resilience against these fluctuations because of the presence of a soil weed bank (Santín-Montanyá et al. 2016).

✉ Unal Asav
unal.asav@gop.edu.tr

[1] Department of Plant Protection, Faculty of Agriculture, Tokat Gaziosmanpaşa University, Tokat, Türkiye

Weed scientists have traditionally concentrated on weed management practices in orchards, employing physical, biological, and chemical control techniques along with cultural treatments (Hammermeister 2016). Chemical weed control can lead to numerous ecological and agricultural problems, such as herbicide resistance, drift, runoff, and harm to non-target organisms (Asav and Serim 2018; Doğan et al. 2022; Esitmez and Işik 2024; Parven et al. 2024). These research areas, except for herbicide resistance, tend to be less appealing and receive less funding from national sources than primary weed control practices do. Focusing on these main topics may lead to the neglect of other research areas that significantly impact weed control practices or weed populations, such as irrigation, grafting, and fertilization.

Irrigation is one of the most crucial agricultural applications in Türkiye, as a substantial portion of the nation's water resources are dedicated to agricultural fields. Despite being classified as a water-stressed country, Turkey allocates 76% of its national water supply to agriculture (Turan and Bayrakdar 2020). Among the irrigation methods, furrow, drip and sprinkle irrigation are the most widely used. Furrow irrigation, the oldest and simplest technique, relies on gravity to distribute water across a significant portion of the field or orchard surface. Owing to its inherent characteristics, this method is highly susceptible to contamination by biological or chemical agents between rows (Kelley and Bruns 1975). Sprinkler irrigation, a relatively newer technique, simulates natural rainfall and can increase water use efficiency (Chauhdary et al. 2024). However, specialized equipment and a power source are needed to pressurize the water, increasing the initial investment cost. The main adverse impact of this system is the potential to encourage fungal and bacterial diseases in orchards (Prodorutti et al. 2024). Drip irrigation, another common method, is designed to conserve water by delivering it slowly near the root zone of crops or orchards (Aras 2006). While this system is more effective in reducing excessive water use, its establishment cost is higher than that of other methods.

Many studies exist on the efficacy of these irrigation systems in various crops and orchards, as well as the irrigation needs of these crops during the growing season. However, there is a notable lack of research on the relationship between irrigation practices and weed density or abundance because the relationship between irrigation practices and weed abundance is complex and multifaceted. Weeds often respond positively to irrigation, similar to crops, orchards, or vineyard, and exhibit growth patterns similar to those of crops or orchards. For example, in tomato fields, reducing furrow irrigation intervals from 9 days to 6 or even 3 days has been shown to significantly increase weed density and dry matter content (Fawad et al. 2022).

This phenomenon underscores the importance of considering weed management in irrigation practices. Furrow irrigation can easily disseminate weed seeds throughout rows, creating an environment conducive to their germination (Wilson 1980). This irrigation method facilitates the spread of exotic plant seeds, which can lead to increased pressure in orchards (Juárez et al. 2010). In contrast, subsurface drip irrigation, which delivers water directly to the root zone of crops, may limit the moisture available to weed seeds, thereby potentially reducing weed emergence and growth (Sutton et al. 2006).

Irrigation is commonly considered an agricultural practice primarily aimed at growing crops or orchards. This study aims to evaluate the effects of furrow, sprinkler, drip, and subsurface drip irrigation on weed flora and the weed seed bank in apple orchards to identify irrigation strategies that support sustainable weed management.

Materials and Methods

Experimental Site

The field trials were conducted from 2021 to 2024 at the Middle Black Sea Transitional Agricultural Research Institute (40.3312 N, 36.5577 E). The orchard consisted of apple trees of the 'Early Red One' variety on the M9 rootstock, which were 7 years old, with 'Mondial Gala' as the pollinator variety, spaced at 4 × 1 m The soil was clay loam, with a pH ranging from 7.56 to 8.06, organic matter from 1.56 to 2.45%, and electrical conductivity (EC) from 0.74 to 0.78 dS/m. The field was located west of Tokat, Turkey, and characterized by transitional climates with severe, harsh winters and dry, warm summers. The experimental field has a continental climate with noticeable seasonal fluctuations. January is the coldest month, with a temperature of –1.6 °C, while August is the warmest, reaching 29.9 °C. July and August typically experienced the least precipitation, whereas April, May, and June reported the highest rainfall. The monthly mean temperature and cumulative rainfall at the site were 12.5 °C and 435.2 mm, respectively. The diammonium phosphate was spread at 1000 kg ha^{-1} annually. Fungicides and insecticides were applied according to regional practices.

Irrigation Treatments

Three types of irrigation techniques were performed in the apple orchard: Surface and subsurface drip irrigation systems were installed along the apple rows. The irrigation systems included a fertilizer tank, sand filter, screen filter, flowmeter, manometers, valves, air valves, pipes, lateral pipes, and drippers. The drippers were spaced 50 cm apart on the surface lines and 40 cm apart on the subsurface lines. The subsurface pipelines were buried at 30 cm soil depths.

For furrow irrigation, water was pumped to furrows that were opened in a V-shaped manner at a 20 cm weight and depth between the apple rows.

The experimental design was a randomized complete block with treatments replicated in three replicates. Treatments included surface drip irrigation, subsurface drip irrigation, and furrow irrigation with a non-treated control. The plot size was 65 × 4 m. A 4-m band between the plots was left as an alley to avoid the impact of irrigation on the plots. The soil in the surface and subsurface drip irrigation treatments was left undisturbed.

Weed Flora and the Seed Bank

The weed flora was determined at the end of June when all the plants reached the flowering stage. The weed flora in each plot was recorded from four 0.25-m^2 quadrats. Species were identified according to the Flora of Turkey and the North Aegean Islands (Davis 1965–1985). The weeds in each plot were cut from the soil surface and placed in paper bags to determine the fresh aboveground weed biomass. The samples were then dried at 72 °C in an oven for 2 days before the dry weight was determined. Weed density (*WD*; 1), weed coverage (*WC*; 2), average weed seed density (*AWSD*; 3) were expressed via the following formulas:

$$WD = \frac{Ni}{n} \tag{1}$$

$$WC = \sum_{i}^{n_w} Ci \tag{2}$$

$$AWSD = \frac{\sum_i^n (Si)}{n_s} \tag{3}$$

where WD, Ni, n, WC, Ci, n_w, $AWSD$, Si, and n_s are the weed density, the total number of weed plants in the sample area (m^{-2}), the number of samples, the weed coverage (%), the percent cover of the i-th weed species, the total number of weed species in the sampling area, the average weed seed density (seeds per sample), the total number of seeds counted in sample i, the number of soil samples taken, respectively.

The weed seed bank was directly found after the separation of all the seeds from the debris and soil particles. Four soil samples from four directions in each plot were collected via a soil borer (10-cm diameter, 10-cm depth) from a depth of 10 cm. The soil samples collected from each plot were sieved (0.8 cm × 0.8 cm) to remove racks, wood, and debris and placed in a plastic bucket filled with tap water for 24 h. The slur samples were gently mixed and washed under tap water using a sieve set from 0.8 cm mesh to 0.1 mesh. Seeds were dried between drying papers and put in Petri dishes under ambient conditions and then stored in a cooler adjusted to +4 °C until classification. Weed species in the seed bank were identified via the aforementioned flora book.

Table 1 Floristic composition of apple orchard over 4 years (2020–2024)

Life form	Weed species	Family	Life form	Weed species	Family
Annual	*Portulaca oleracea* L.	Portulacaceae	Annual	*Avena fatua* L.	Poaceae
	Amaranthus retroflexus L.	Amaranthaceae		*Conyza canadensis* (L.) CRONQUIST	Asteraceae
	Chepodium album L.	Amaranthaceae		*Papaver rhoeas* L.	Papaveraceea
	Capsella bursa pastoris (L.) Medik.	Brassicaceae	Perennial	*Convolvulus arvensis* L.	Convolvulaceae
	Geranium dissectum L.	Geraniaceae		*Trifolium pratense L.*	Fabaceae
	Solanum nigrum L.	Solanaceae		*Plantago lanceolata* L.	Plantaginaceae
	Lolium temulentum L.	Poaceae		*Hypericum perforatum* L.	Hypericaceae
	Setaria verticillata L.	Poaceae		*Rubus idaeus* L.	Rosaceae
	Sonchus oleraceus L.	Asteraceae		*Cirsium arvense* (L.) Scop.	Asteraceae
	Polygonum aviculare L.	Polygonaceae		*Medicago sativa* L.	Brassicaceae
	Lactuca serriola L.	Asteraceae		*Euphorbia sp.*	Euphorbiaceae
	Veronica persica POIRET	Plantaginaceae		*Rumex crispus* L.	Polygonaceae
	Lamium amplexicaule L.	Lamiaceae		*Tragopogon pratensis* L.	Asteraceae
	Echinochloa crus-galli (L.) P. Beauv.	Asteraceae		*Taraxacum officinale* (L.) Weber.	Asteraceae
	Fumaria officinalis L.	Papaveraceae		*Echium vulgare* L.	Boraginaceae
	Stellaria media (L.) Vill.	Caryophyllaceae		*Sorghum halepense* (L.) PERS.	Poaceae
	Hordeum vulgare L.	Poaceae	Geophyte	*Poa bulbosa* L.	Poaceae

Statistical Analysis

The data obtained from the three irrigation systems—weed abundance, weed biomass, and weed soil bank—were analyzed via one-way analysis of variance (ANOVA) to evaluate the effects of the irrigation systems. Before the statistical analysis, the Shapiro–Wilk test was used to check for normality, and the raw data were not transformed. To compare means, Fisher's protected least significant difference test was applied at the 5% significance level. The Agricolae package (Mendiburu and Yaseen 2020) was used in R (RStudio Team 2024).

Results

Floristic Composition

The experimental field presented a rich diversity of weed species. An evaluation of the weeds according to life form revealed that 20 species were annual, 13 were perennial, and one was tuberous (Table 1). Observations have indicated that annual weeds generally occur at higher densities and cover a larger area than perennial weeds do. Among these, *Portulaca oleracea* L., *Amaranthus retroflexus* L., and *Chenopodium album* L. were the most dominant species, appearing in nearly all the experimental plots with varying densities. In contrast, species such as *Hypericum perforatum* L., *Medicago sativa* L., *Echinochloa crus-galli* (L.)

Table 2 Weed density response to irrigation treatment during 2021–2024 (weed plant m^{-2})

Year	Surface drip		Subsurface drip		Furrow		Control	
	Weed density	PC	Weed density	PC	Weed density	PC	Weed density	PC
2021	6.67 ± 0.88a*B**	47.6	7.67 ± 0.88aB	54.8	15.33 ± 0.67aA	109.5	14 ± 0.58aA	–
2022	5.670.33 ± aB	50.0	6.33 ± 0.33abB	55.9	11.67 ± 0.67abA	103.0	11.33 ± 0.67aA	–
2023	7.330.33 ± aB	59.4	6.67 ± 0.33abB	54.1	12.67 ± 0.88abA	102.8	12.33 ± 0.88aA	–
2024	6.330.33 ± aB	51.3	4.33 ± 0.33bC	35.1	11.33 ± 0.33bA	91.9	12.33 ± 0.33aA	–

PC Percent of the control (%)

*The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($P < 0.05$)

**The letters represent statistical significance, where different letters indicate significant differences between irrigation treatments ($P < 0.05$)

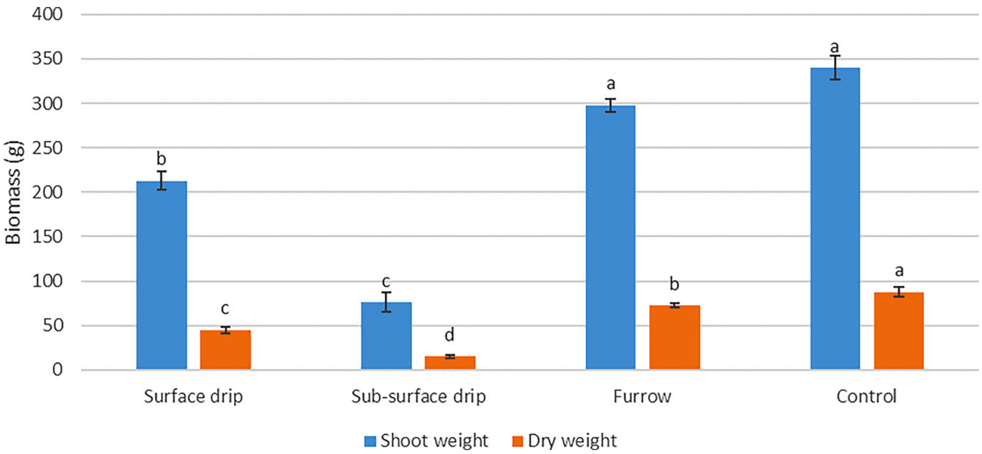

Fig. 1 Biomass (shoot and dry weight) response to different irrigation methods in 2024. Error bars indicate standard errors, and letters above the bars represent statistical significance, where different letters indicate significant differences between irrigation treatments ($P < 0.05$)

Table 3 Weed coverage response to irrigation treatment during 2021–2024 (%)

Year	Surface drip		Subsurface drip		Furrow		Control	
	Weed Cov	PC	Weed Cov	PC	Weed Cov	PC	Weed Cov	PC
2021	62.82 ± 0.17ab*B**	69.2	49.73 ± 1.29abC	54.8	88.18 ± 3.47aA	97.1	90.82 ± 1.10abA	–
2022	78.28 ± 3.04aB	83.1	57.99 ± 1.11aC	61.6	89.33 ± 3.98aA	94.9	94.17 ± 1.78aA	–
2023	67.33 ± 2.19abC	74.5	53.34 ± 0.76abD	59.1	82.99 ± 1.77abB	91.9	90.33 ± 4.41abA	–
2024	51.28 ± 2.42bC	63.0	45.95 ± 0.59bC	56.4	71.4 ± 4.07bB	87.7	81.44 ± 1.02bA	–

Weed Cov Weed coverage (%), *PC* Percent of the control (%)

*The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($P < 0.05$)

**The letters represent statistical significance, where different letters indicate significant differences between irrigation treatments ($P < 0.05$)

Table 4 Average weed seed density (AWSD) in the soil bank during 2021–2023 (%)

Year	Furrow		Surface drip		Subsurface drip		Control	
	AWSD	RC	AWSD	RC	AWSD	RC	AWSD	RC
2021	119 ± 27 a*A**	0	151 ± 58 aA	0	275 ± 38 aA	0	124 ± 27 aA	0
2022	206 ± 20 aB	73	269 ± 21 aAB	78	380 ± 43 aA	38	287 ± 42 bAB	132
2023	272 ± 71 aA	128	279 ± 126 aA	85	418 ± 30 aA	52	357 ± 8 bA	189

*The letters represent statistical significance, where different letters indicate significant differences between years in the same treatment ($P < 0.05$)
**The letters represent statistical significance, where different letters indicate significant differences between irrigation treatments ($P < 0.05$), *RC* Relative change according to the *AWSD* in 2021

P. Beauv., *Avena fatua* L., *Tragopogon pratensis* L., and *Echium vulgare* L. were present at much lower densities.

The interaction effect between year and irrigation practices was found to be significant in terms of both the weed density and the weed coverage area. Therefore, the effects of each irrigation practice were analyzed separately by year. The greatest weed density was detected in the control and flood-irrigated plots (Table 2). Notably, no statistically significant difference was found between the years for the control and surface drip irrigation plots. However, in the furrow and subsurface drip irrigation plots, the weed density steadily decreased over time. Compared with the control and flood irrigation methods, both the surface drip and subsurface drip irrigation methods resulted in significantly lower weed infestations. By the end of the fourth year, compared with the control, furrow, and surface drip irrigation, subsurface drip irrigation led to a 64%, 62%, and 32% reduction in weed densities, respectively. These findings suggest that subsurface drip irrigation is particularly effective at reducing weed growth over time, offering a more sustainable option for long-term weed management.

The highest weed biomass was found in the control plots where no irrigation was applied (Fig. 1). Although the weed biomass in the plots irrigated by furrow was lower than that in the control due to strong competition between the weeds, the difference was significant for dry weight but not for fresh weight. Compared with the control, surface drip irrigation resulted in a 37% decrease in fresh weight and a 49% decrease in dry weight of weeds. When subsurface drip irrigation was applied, the fresh biomass was 78%, 74%, and 64% lower, and the dry biomass was 82%, 79%, and 66% lower than those in the control, furrow, and surface drip irrigation treatments, respectively.

The impact of irrigation practices on weed coverage was more prominent than that on weed density. Compared with the control, all irrigation treatments led to a reduction in weed coverage (Table 3). However, the extent of this reduction varied across the different irrigation methods. Furrow irrigation resulted in only a modest decrease in weed coverage, whereas surface and subsurface drip irrigation resulted in more substantial reductions. The influence of irrigation on weed growth became increasingly evident from the third year onward, reaching its peak by the fourth year. By the end of the study, plots with furrow, surface drip, and subsurface drip irrigation had 12%, 37%, and 44% less weed coverage on the soil surface, respectively, than did the control. These findings highlight the superior efficacy of surface and subsurface drip irrigation in controlling weed coverage over time. The results suggest that as irrigation systems become more efficient, such as with subsurface drip irrigation, they not only conserve water but also contribute significantly to reducing weed proliferation, particularly after the third year of application. This highlights the potential of advanced irrigation techniques to enhance both crop management and long-term sustainability in agricultural practices.

The annual weed seed density (AWSD) in the soil consistently increased each year across all irrigation treatments, including the control (Table 4). In the control plots, the AWSD increased significantly, with a 132% increase by the second year and a 189% increase by the third year, highlighting the substantial accumulation of weed seeds in untreated soil. Among the irrigation systems, the furrow-irrigated plots presented the highest AWSD after the control, with a 128% increase by the second year, suggesting that this irrigation method might create favorable conditions for weed seed persistence and dispersal. The surface drip irrigation plots presented a moderate increase in AWSD, with a 78% increase in the second year and an 85% increase by the third year, indicating that while this irrigation method contributed to weed seed accumulation, its impact was less pronounced than that of furrow irrigation. Notably, the subsurface drip irrigation plots presented the lowest increase in AWSD, with only a 38% increase in the second year and a 52% increase by the third year. This relatively low level of increase in the subsurface drip plots suggests that this irrigation method may be less conducive to weed seed accumulation, possibly because of reduced surface moisture, which limits conditions favorable for weed seed germination and spread.

Discussion

Crops are more adversely affected by drought than are weeds. The reduction in growth of cultivated plants under drought conditions is generally greater than that observed in weeds. (Freitas et al. 2019). Research has shown that irrigation is a vital factor influencing weed flora dynamics (Shrestha et al. 2007). By increasing soil moisture, irrigation creates a favorable environment that supports the growth of both cultivated plants and weeds. The impacts of irrigation and other factors, such as weed management and weed interactions, on weed populations, have been examined extensively across various dimensions, especially in field crops (Khaffagy et al. 2022; Fawad et al. 2022). These studies indicate that irrigation can significantly alter the weed flora in row crops such as cotton (Bükün 2005; Arslan 2018; Serim et al. 2023).

Although many factors can change weed flora in orchards, researchers have focused primarily on the impact of floor management practices or fertilizers (Hussain et al. 2020; Licznar-Małańczuk and Slobodianyk 2021; Miñarro 2012). However, research on the influence of irrigation on weed populations within fruit orchards remains limited. Jordan and Russell (1981) reported that annual weeds resulted in significant 'Valencia' orange yield loss and deterioration of quality parameters, including juice, soluble solids, acid, and leaf nitrogen. The adverse impacts of *Cynodon dactylon* on yield and quality were greater than those of annual weeds, except for the leaf nitrogen content. They compared the effects of furrow irrigation and sprinkler irrigation on yield and quality but were not interested in their interactions. Andersen et al. (2013) reported that the irrigation schedule had no effect on the number of plant species in apple orchards but did affect the coverage of plants. On the other hand, Shrestha et al. (2007) found that subsurface drip irrigation nearly prevented all weed emergence in furrows. They also reported that weed density was significantly lower in this irrigation system than in furrow irrigation. In the present study, the weed count under furrow irrigation was greater than that under the control (rainfed plots), whereas the weed count under surface drip irrigation and subsurface drip irrigation was lower than that under the control, similar to the findings of Shrestha et al. (2007). In contrast to the results of Andersen et al. (2013), weed coverage in all irrigation treatments was lower than that in the control. This discrepancy, especially in furrow irrigation, may be caused by competition between more newly emerged weed seedlings.

Furrow irrigation channels are vulnerable to weed contamination if they are built on the soil surface. The irrigation water supplied by these channels is highly important for dispersing weed seeds to other parts of fields or orchards (Kelley and Bruns 1975). Moreover, compared with drip irrigation, furrow irrigation can carry more weed seeds from exotic plants than can native plants (Juárez et al. 2010). Juárez-Escario et al. (2013) reported that the floristic and functional compositions of orchards were more affected by irrigation systems than by weed control practices. The impact of irrigation on weed flora was investigated by Grattan et al. (1988), who reported that irrigation was a significant factor in controlling annual weeds in summer crops and that the use of subsurface drip irrigation instead of sprinkler or furrow irrigation provided acceptable weed control via herbicides, similar to the findings of this study. These findings indicate that subsurface drip irrigation can be a more effective method for minimizing weed growth, potentially reducing the reliance on chemical weed control and its associated ecological impacts.

Changes in the soil moisture level affect not only the weed flora but also the biomass of weeds. Plants experiencing water stress activate different mechanisms to reduce water consumption (Farooq et al. 2009). Reducing leaf area is among the most important of these mechanisms (Legg et al. 1979). While this adaptation helps conserve water, it also decreases plant growth and biomass production. This situation was observed in the plots with drip irrigation and subsurface drip irrigation in the experimental area. Grattan et al. (1988) indicated that subsurface drip irrigation without herbicide treatment might suppress the growth of weed biomass as much as herbicides under furrow irrigation conditions. Similarly, Shrestha et al. (2007) stated weed biomass was significantly affected by irrigation systems, and nine times greater amounts of biomass were detected in furrow irrigated plots than in subsurface drip irrigated plots, similar to the results of this study.

Conclusion

Drought, shifts in precipitation patterns, and extreme temperature necessitate the exploration of more effective strategies for addressing the water requirements of apple and optimizing the use of existing irrigation resources. Given that the morphology and physiology of weeds are influenced by changing climatic conditions, it is imperative to conduct researches on weed management in orchards equipped with irrigation systems under varying scenarios. Converting irrigation systems in apple orchards from furrow irrigation to surface or subsurface drip irrigation not only enhances water-use efficiency but also reduces environmental humidity, which, in turn, helps decrease the incidence of plant diseases. Additionally, the implementation of subsurface drip irrigation as a weed management strategy can limit weed growth in apple orchards, thereby promoting essential ecosystem services. This approach can expand habitats for pollinating species, thus increasing their activity and effectiveness while also creating supportive environments for other beneficial organisms.

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Author Contribution The conception and writing of the manuscript belongs to author.

Availability of Data and Material The data generated during the current study are available from the corresponding author on reasonable request.

Conflict of interest U. Asav declares that he has no competing interests.

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