



# The use of cover crop for weed suppression and competition in limited-irrigation vineyards

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**Abstract** Soil degradation and climate change put stress on cultivated plants necessitating sustainable weed management practices that reduce herbicide usage and environmental pollution. Cover cropping has emerged as a viable alternative since it has many advantages over traditional herbicides in terms of cultivated plants, soil health, and weed suppression. This three-year study (2020–2023) aimed to examine the performance of cover crops (grass pea, berseem clover, common vetch+triticale, and phacelia) in a drip-irrigated vineyard with restricted water supply in southern Türkiye. The parameters monitored to evaluate the competition between cover crops and weeds were coverage, height, light intensity, shade capacity, dominance, density, and biomass. The common vetch+triticale mixture displaying the highest suppression rates followed by grass pea and phacelia. Cover crops' height was inversely associated with weed biomass, which suggests that they have the potential to be effective weed management tools because it may provide substantial shading as well as competing performance. The findings of the study highlights the importance of environmentally friendly practices as cover cropping in reducing herbicide reliance and in promoting sustainable vineyard agriculture. Furthermore, the observations of cover crops

align with the objectives of the Green Deal suggest a promising approach that enhances soil health be considered to conserve water and foster a more resilient agricultural ecosystem.

**Keywords** Climate change · Green Deal · Integrated weed management · Mediterranean basin · Southern Türkiye

## Introduction

Grapevines (*Vitis vinifera* L.) are one of the primary agricultural crops globally holding significant commercial and economic importance. Products from cultivated grapevines are utilized in various food sectors, and their consumption continues to increase. Although the grapevine cultivation area in Türkiye has decreased since 2010, production has increased by 16% as in 2021 in which Türkiye accounted for approximately 6% of the world's grapevine cultivation area and production (OIV, 2023). Irrigation is widely applied in many grapevine cultivation areas in Türkiye, whereas grapevine cultivation in Europe is predominantly practiced in regions having sufficient rainfall (Costa et al., 2016). However, as a result of global climate change, rising temperatures have led to increased water consumption and input costs, posing challenges for producers and leading to some grapevine fields being abandoned, as economically viable products are preferred in cultivation (Vigl et al.,

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2018; Van Leeuwen et al., 2019; Fraga et al., 2020; Candiago et al., 2023). Furthermore, the decreasing precipitation driven by global climate has resulted in changes in cultivated products' contents (e.g., sugar content, anthocyanin levels, water content, etc.), causing declines in product quality (Van Leeuwen et al., 2009).

The effects of global climate change, soil degradation and changes in soil composition, increase pest populations, and insufficient pest control methods put stress on cultivated plants (Bernardo et al., 2018; Raza et al., 2019). Biotic factors like weeds compete for nutrients, light, and water, negatively affect the yield and quality of both young and mature vineyards if left unmanaged in vineyards (Byrne & Howell, 1978; Bordelon & Weller, 1997; Oerke, 2006; Ekwealor et al., 2009). In addition to the impacts of global climate and irrigation, a decrease in the competitive ability of cultivated plants might lead to an increase in harmful weed populations (Guerra et al., 2021, 2022a). The farmers, on the other hand, may seek higher yields in short periods resulting in greater herbicide consumption for weed control (Kudsk & Streibig, 2003). Furthermore, the increasing use of herbicides threatens the health of people and animals by causing pollution and environmental deterioration. (Rashid et al., 2010). However, there are other noteworthy weed control methods to reduce herbicide use, such as mechanical control, cover cropping, mulching, burning, hot water treatments, and the use of light and sound waves (Bugg et al., 2000; Shrestha et al., 2012). In light of these similar findings, the Green Deal has focused on alternative pest control methods (bioherbicides, mulching, cover crops, etc.) to reduce the pesticide impact on the environment (Winter et al., 2018; Hall et al., 2020; Guerra et al., 2022a).

Cover crops have been reported to be indispensable in suppressing weed populations, improving soil structure, increasing soil organic-matter content, reducing soil erosion, and enhancing microbiological functions, nitrogen fixation, and biodiversity, which in turn lowers water and moisture loss in cultivated areas (Malik et al., 2000; Bond & Grundy, 2001; Dabney et al., 2001; Sainju et al., 2002; Thiessen-Martens et al., 2005; Blanchart et al., 2006; Uludag et al., 2006; Monteiro & Lopes, 2007; Kruidhof et al., 2008; Steenwerth & Belina, 2008; Demir & Işık, 2019, 2020; Cabrera-Pérez et al., 2022; Guerra et al.,

2022b). In Türkiye, several studies have been conducted on cover crops testing their potential to serve as alternatives to conventional herbicides for various crops, such as citrus (Kolören & Uygur, 2006; Temel et al., 2011), apricots (Tursun et al., 2018), apples (Işık et al., 2018), kiwis (Işık et al., 2013), vegetables (Işık et al., 2009; Mennan et al., 2020), olive (Uyar, 2022) and vineyards (Kaçan & Boz, 2014). However, further studies are needed, and their implementation is crucial for farmers to align with the regulations of the Green Deal.

Thus, new era under climate change and Green Deal require more environmentally sound strategies and implementations. The aim of this study is to help to develop a sustainable weed control management in vineyards to cope with drought. In order to achieve the objectives of the study the competitive abilities and performance of some cover crop species namely *Lathyrus sativus* L., *Phacelia tanacetifolia* Benth., *Trifolium alexandrinum* L., and *Vicia sativa* L. + *Triticale* sp. mixture against weed species in drip-irrigated vineyards with restricted water supply were examined.

## Materials and methods

The experiments were conducted in a drip-irrigated vineyard with restricted water supply in Adana Province located in the Çukurova Region of southern Türkiye, between 2020 and 2023 (Table 1).

Cover crop species were selected according to earlier studies in various perennial crops in Türkiye (Kolören & Uygur, 2006; Temel et al., 2011; Kaçan & Boz, 2014; Tursun et al., 2018; Demir & Işık, 2020; Mennan et al., 2020). They were grass pea (*Lathyrus sativus* L.; LTHSA), berseem clover (*Trifolium alexandrinum* L.; TRFAL), common vetch + triticale (*Vicia sativa* L. + *Triticale* sp.; VICSA+TTLRI), and phacelia (*Phacelia tanacetifolia* Benth.; PHCTA). The experimental design was randomized complete block design, with three replicates. A block was established on a row including five plots (four cover crops and a check without cover crop). The width of a block was 1 m where trunks were aligned with the centre. Plots in a block were fixed for three years and cover crops randomly assigned in the beginning of the experiment. A plot was 6 m in length along the row and contained three trunks. The cover crops were seeded in corresponding plots at the end of November every year (Table 2) and cut when

**Table 1** Monthly mean temperature, rainfall, and humidity during the vine growing season at the experimental location during the experiment in Adana, Türkiye

Months	Temperature (°C)				Rainfall (mm)				Humidity (%)			
	2020	2021	2022	2023	2020	2021	2022	2023	2020	2021	2022	2023
January	-	11.7	8.9	11.6	-	130.1	211.6	14.8	-	63.6	66.2	63.5
February	-	13.1	12.4	10.2	-	23.6	78.2	52.5	-	61.5	71.7	55.6
March	-	14.0	10.8	15.8	-	48.8	96.5	92.0	-	65.5	58.5	71.2
April	-	18.4	20.0	17.8	-	47.4	2.7	91.1	-	68.6	57.1	68.7
May	-	23.9	22.0	22.6	-	3.0	7.9	54.1	-	64.8	61.8	62.6
November	17.0	17.4	17.7	-	55.5	46.6	58.9	-	59.5	66.4	67.9	-
December	13.4	11.9	13.9	-	27.1	201.0	29.0	-	63.9	66.7	73.3	-

50% of individuals bloomed which corresponded early May. Plots were irrigated applying half of 200 mm of water per month which is calculated water needs of each trunk, starting from April via sprinklers hanged 50 cm above the soil level that were aligned with 15 cm distance from each other along centre of row.

Two 1 m<sup>2</sup> areas were set to align with two trunks in the plots to use measurements at 80th, 110th and 140th days after sowing cover crops (Nkoa et al., 2015). In these areas, the number of cover crop individuals and weeds according to species were counted and presented as density of cover crop or weeds (plants m<sup>-2</sup>). In addition, plant height (cm) and weed light intensity (at noon) were measured in each square and averages were calculated. Plant coverage

(%) for weeds and cover crops were examined in whole plot. After the measurements on 140th day the weeds and cover crops were harvested by cutting at the soil surface and placed in paper bags, kept in a drying cabinet at 105 °C for 24 h, and then their dry weights were measured and presented as dry biomass (g m<sup>-2</sup>). Weeds were identified according to the Flora of Turkey by Davis (1965–1988). In order to show cover crop competitive ability, cover crop shade capacity (%) (see Eq. 1) and cover crop dominance (%) (see Eq. 2) were calculated. The shade percentage was determined using a lux meter with measurements taken at noon when their growth completely stopped at the start of the generative development stage of the cover crops.

$$\text{Weed light intensity}(\%) = 100 - \left[ \frac{\text{Top of the cover crops} - \text{Top of the weeds}}{\text{Control}} \times 100 \right] \quad (1)$$

*Cover crop shade capacity (%) = 100 – Weed light intensity (%)*

**Table 2** The cover crops, cultivars, and seeding rates

Cover crops	Scientific name	EPP codes	Cultivar	Seeding rate (kg ha <sup>-1</sup> )
Grass pea	<i>Lathyrus sativus</i> L. (Fabaceae)	LTHSA	Gürbüz-2001	200
Phacelia	<i>Phacelia tanacetifolia</i> Benth. (Boraginaceae)	PHCTA	Sağlamtimur	15
Berseem clover	<i>Trifolium alexandrinum</i> L. (Fabaceae)	TRFAL	Derya	30
Common vetch + Triticale	<i>Vicia sativa</i> L. + <i>Triticale</i> sp. (Fabaceae + Poaceae)	VICSA + TTLRI	Yücel + Tacettinbey	120 + 150

$$\text{Cover crop dominance(\%)} = 100 - \left[ \frac{\text{Weed coverage(control)}}{\text{Cover crop coverage}} \times 100 \right] \quad (2)$$

The data obtained from the experiment were analysed using SPSS. For the multiple comparison tests, the data of the applications (depending on the observation periods) were compared and grouped under a statistically significant level of 0.05 using the Duncan Test (ANOVA) (SPSS, 2015).

## Results

### Weed species in the experimental site

A total of 24 weed species was determined in experimental plots during three years. The densest species were *Veronica arvensis* L., with 10.00 plants m<sup>-2</sup> (27.59%), followed by *Fumaria officinalis* L. with

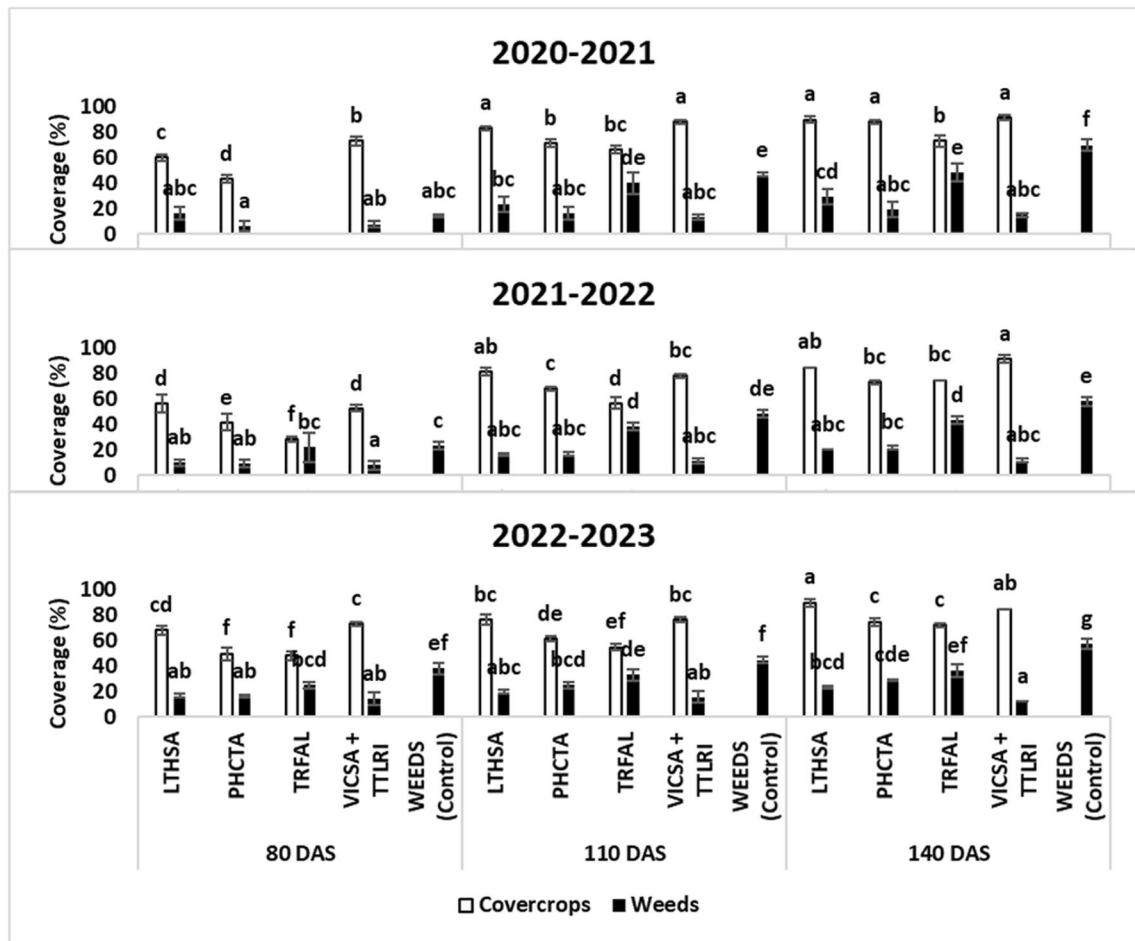
7.77 plants m<sup>-2</sup> (21.44%) and *Avena sterilis* L. with 3.27 plants m<sup>-2</sup> (9.03%) (Table 3).

Comparison of obtained criteria data from cover crops and weeds

The highest coverage of cover crops was observed at 140 DAS (before harvesting). In the first year, at 140 DAS, all cover crop coverage rates ranged between 88.30% and 91.70% (except for TRFAL, with 73.30%). In the second and third years, LTHSA was observed to have reached the highest coverage rates (85.00% and 90.00%, respectively), followed by VICSA + TTLRI (91.70% and 85.00%, respectively) (Fig. 1). Due to the low precipitation and dry conditions during the first year, the cover crop coverage at 110 DAS and 140 DAS effectively suppressed weed area coverage. During the second and third years seeing greater rainfall reductions in the cover crop area coverages were noticed on the observation dates; only LTHSA and

**Table 3** Weed species of the experimental area and their relative proportions (average of years)

Weeds	EPP0 Codes	Average (plants m <sup>-2</sup> )	Proportion (%)
<i>Allium</i> spp.	ALLSS	0.30	0.83
<i>Ammi majus</i> L.	AMIMA	0.17	0.48
<i>Avena sterilis</i> L.	AVEST	3.27	9.03
<i>Calendula arvensis</i> (Vaill.) L.	CLDAR	2.57	7.09
<i>Capsella bursa-pastoris</i> (L.) Medik.	CAPBP	0.25	0.70
<i>Cichorium intybus</i> L.	CICIN	0.04	0.10
<i>Convolvulus arvensis</i> L.	CONAR	0.83	2.30
<i>Conyza</i> spp.	CNDSS	0.05	0.14
<i>Crepis foetida</i> L.	CVPFO	0.15	0.41
<i>Cynodon dactylon</i> (L.) Pers.	CYNDA	2.14	5.89
<i>Erodium</i> spp.	EROSS	0.04	0.10
<i>Fumaria officinalis</i> L.	FUMOF	7.77	21.44
<i>Galium aparine</i> L.	GALAP	<0.01	0.01
<i>Geranium dissectum</i> L.	GERDI	<0.01	0.01
<i>Lactuca serriola</i> L.	LACSE	0.01	0.03
<i>Lamium amplexicaule</i> L.	LAMAM	0.88	2.44
<i>Mercurialis annua</i> L.	MERAN	2.82	7.78
<i>Senecio vernalis</i> Waldst. & Kit.	SENVE	3.14	8.67
<i>Silene</i> spp.	SILSS	0.96	2.66
<i>Sinapis arvensis</i> L.	SINAR	0.08	0.21
<i>Sonchus oleraceus</i> L.	SONOL	0.02	0.07
<i>Sorghum halepense</i> (L.) Pers.	SORHA	0.52	1.43
<i>Veronica arvensis</i> L.	VERAR	10.00	27.59
<i>Vicia</i> spp.	VICSS	0.21	0.58



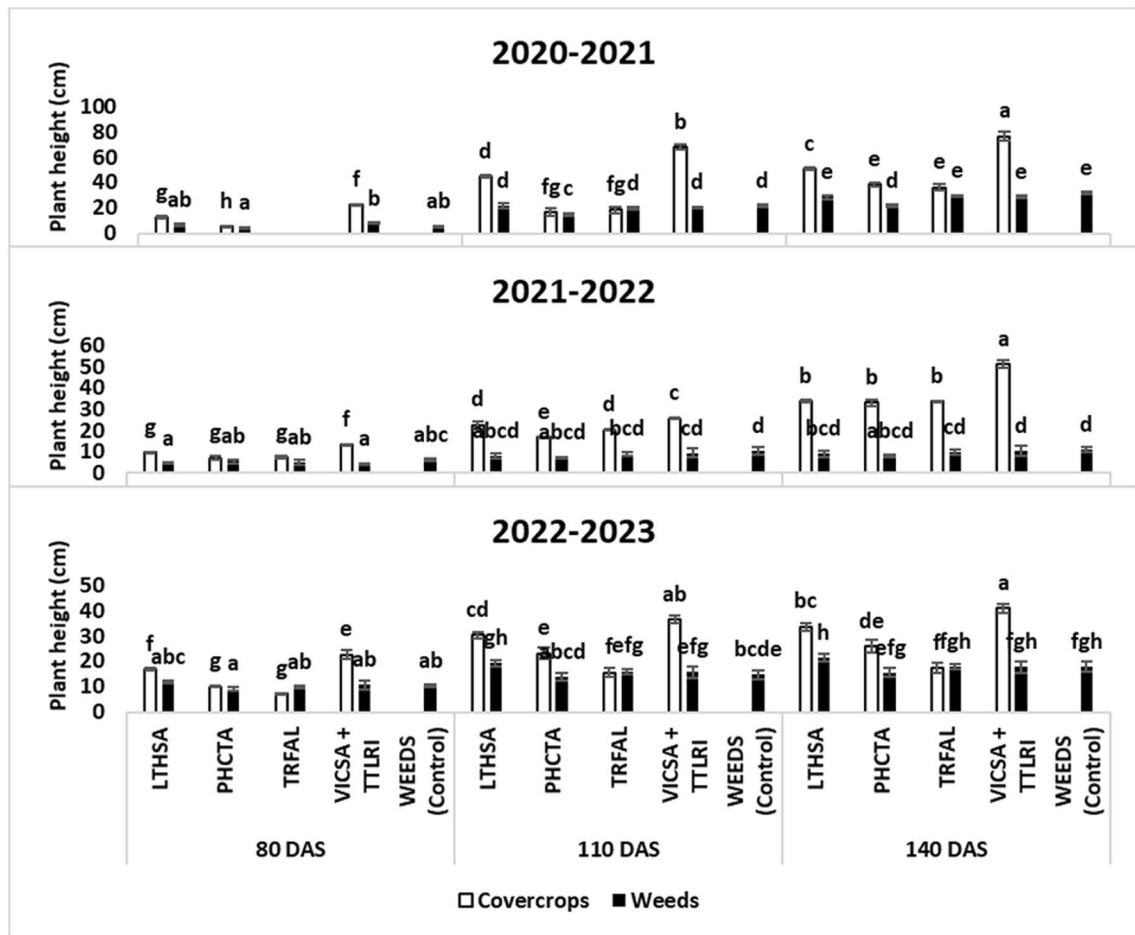
**Fig. 1** Annual cover crop and weed coverage (%) parameters at 80, 110, and 140 days after sowing (DAS)

VICSA+TTLRI values were close to each other. In the first year, due to the drought, TRFAL germination was delayed at 80 DAS, although the germination rate increased, thereafter (Fig. 1).

When the weed area coverages were compared among the cover crops, it was observed that the cover crops with the highest weed suppression in the first year were PHCTA (weed coverage (WC): 6.30%) and VICSA+TTLRI (WC: 7.70%) at 80 DAS. In the second and third years, LTHSA (WC: 10.00% and 16.70%, respectively), PHCTA (WC: 9.30% and 16.00%, respectively), and VICSA+TTLRI (WC: 8.00% and 14.30%, respectively) showed the highest weed suppression, at 80 DAS. In the third year, at 110 and 140 DAS, the cover crop VICSA+TTLRI (WC: 15.70% and 12.50%, respectively) continued

suppressing the weed coverage at the same level throughout the observation period. The weed control plots with weeds (WC: 70.00%, 58.30%, 57.50% at 140 DAS, respectively) showed the highest area coverages on all observation dates (Fig. 1).

With regard to the heights of the cover crops, the highest cover crop height was seen with the VICSA+TTLRI mixture (ranging from 40.90 to 76.50 cm) throughout the observation period. LTHSA showed the second-highest height (reaching 51.00 cm at 140 DAS during the 2020–2021 season) and the lowest height (9.50 cm at 80 DAS during the 2021–2022 season). TRFAL had the lowest height, due to its plant characteristics. The tall height in the VICSA+TTLRI mixture was attributed to TTLRI, which belongs to the Poaceae family (Fig. 2).



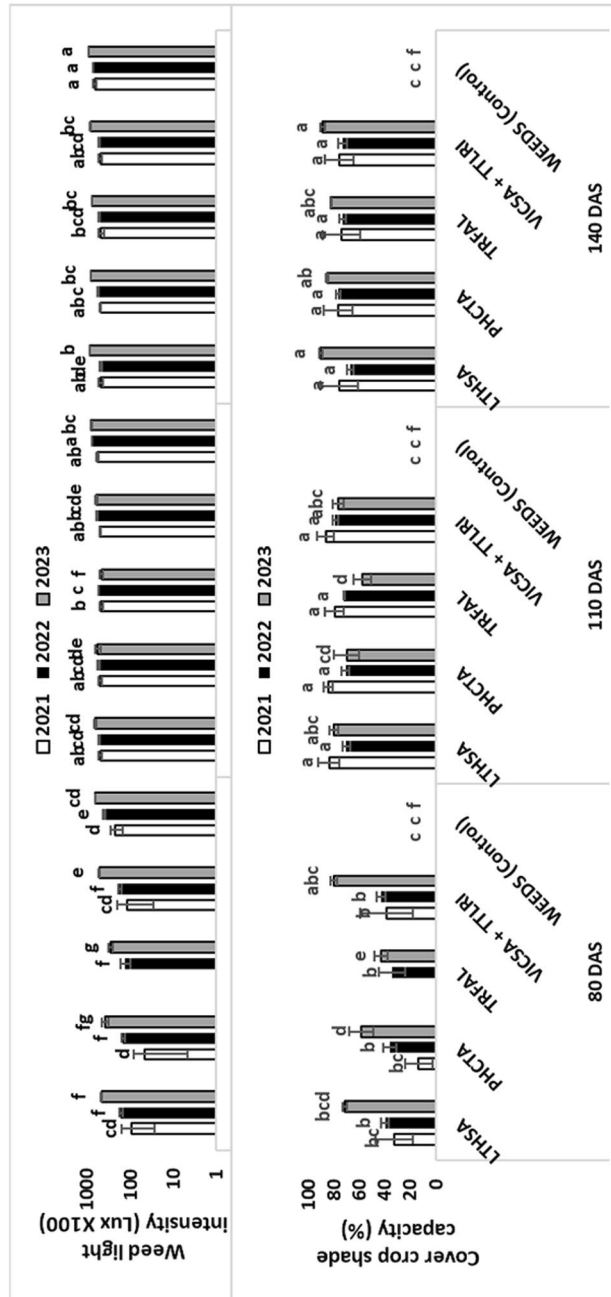
**Fig. 2** Observations of the plant heights (cm) during the experiment

On the other hand, statistically significant differences were found between the treatments when the height of the weeds within the cover crops were compared. The weed heights were the lowest at 80 DAS throughout the vineyard season, and they were higher at 110 and 140 DAS, depending on their development. The weed heights within the cover crops were similar to each other: before the harvesting at 140 DAS, the weed heights in the cover crop plots were recorded to be the same level as compared to the control plots (31.70 cm, 10.80 cm, and 17.90 cm for cover crops VICSA + TTLRI, PHCTA, and TRFAL, respectively). Thus, VICSA + TTLRI, PHCTA, and TRFAL cover crops were effective in suppressing weed heights (Fig. 2).

Figure 3 displays the plant height values. The measurements were taken during the flowering and

generative or vegetative development stages since broadleaf and narrow-leaf weeds normally do not germinate and emerge simultaneously.

Cover crops competed with weeds for shading. This shows that cover crop growth develops faster than weeds under suitable climatic conditions. From 80 to 140 DAS during the 2020–2023 cultivation season, the cover crops and weeds reduced the shading duration. At the 110 and 140 DAS, the differentiation in shading duration between cover crops and weeds increased in all plots. As the cover crops developed, the shading time for weeds decreased, which increased shading rates. As the difference between the cover crops and weeds in lux illumination values increased, the shading rate of cover crops increased as well. In all of the evaluations, the VICSA + TTLRI and LTHSA plots showed the highest shading,



**Fig. 3** Weed light intensity (Lux) and cover crop shade capacity (%) measures of the experiment

followed by PHCTA and TRFAL. After 80 DAS, although the cover crops continued to compete with weeds in terms of shading duration and shading effect, the same effect did not exist in the observations at the 110 and 140 DAS (Fig. 3).

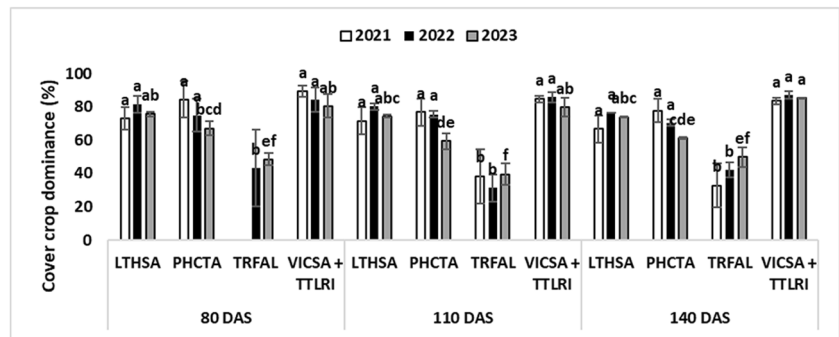
Figure 4 presents the cover crop dominance. They were percentages of cover crop and weed coverage obtained during the experimentation.

As shown in the Figure the TRFAL was holding the lowest values during all of the years. We observed that VICSA+TTLRI, LTHSA, and PHCTA suppressed weed coverage areas by 60–80%, that the highest suppression rate of weed coverage was achieved by VICSA+TTLRI. We assumed that reductions in

suppression rates would be observed with LTHSA and PHCTA in 2023 due to the variations in precipitation and environmental factors. (Fig. 4).

The highest weed density on all plots was naturally obtained from the weed-infested control plots (ranging from 1.80 to 5.00 plants m<sup>-2</sup>) on different counting dates before the cover crops were harvested. The effects of experiments between 2021 and 2023 were grouped under three titles; efficiency, density and weed density. As shown in Table 4, the lowest efficiency was observed in 2021, with 4.07 plants m<sup>-2</sup>; weed density of LTHSA of during 2022 and 2023 TRFAL had a density of 2.10 plants m<sup>-2</sup>; and 2.07 plants m<sup>-2</sup>.respectively.

**Fig. 4** Cover crop dominance (%) obtained during the 80th, 110th, and 140th days after sowing (DAS)



**Table 4** The effects of the cover crops on weed density (plants m<sup>-2</sup>) at 80, 110, and 140 days after sowing (DAS)

DAS	Cover crops	2021	2022	2023
80	LTHSA	3.77 (±0.49) bc	1.10 (±0.00) ab	1.20 (±0.17) abc
	PHCTA	1.50 (±0.91) a	0.57 (±0.27) a	1.20 (±0.30) abc
	TRFAL	-	1.20 (±0.23) ab	1.63 (±0.22) abcd
	VICSA + TTLRI	1.30 (±0.26) a	0.90 (±0.12) ab	0.87 (±0.27) a
	WEEDS (Control)	3.13 (±0.33) abc	1.80 (±0.06) bcd	2.30 (±0.17) de
110	LTHSA	3.93 (±0.49) bc	1.33 (±0.07) abc	1.33 (±0.19) abc
	PHCTA	1.63 (±0.95) a	0.93 (±0.44) ab	1.60 (±0.36) abcd
	TRFAL	2.57 (±0.64) ab	1.63 (±0.39) bc	1.87 (±0.35) bcde
	VICSA + TTLRI	1.37 (±0.29) a	1.13 (±0.09) ab	0.93 (±0.24) a
	WEEDS (Control)	4.77 (±0.23) c	2.53 (±0.22) d	2.70 (±0.23) e
140	LTHSA	4.07 (±0.49) bc	1.73 (±0.18) bcd	1.53 (±0.23) abcd
	PHCTA	1.77 (±0.98) a	1.23 (±0.49) abc	1.97 (±0.38) bcde
	TRFAL	2.67 (±0.64) ab	2.10 (±0.42) cd	2.07 (±0.39) bcde
	VICSA + TTLRI	1.37 (±0.29) a	1.33 (±0.09) abc	1.03 (±0.20) ab
	WEEDS (Control)	5.00 (±0.21) c	3.37 (±0.28) e	3.63 (±0.12) f
		df=41 F=5.351 p=0.000	df=44 F=7.042 p=0.000	df=44 F=7.633 p=0.000

\* The average means of letters are different from each other at the  $p < 0.05$  level of statistical significance, according to Duncan’s Multiple Comparison Test



**Table 5** Cover crop biomass and the effects of the cover crops on weed dry biomass at 140 days after sowing (DAS)

Treatments	2021		2022		2023	
	Cover crops	Weeds	Cover crops	Weeds	Cover crops	Weeds
LTHSA	430.00 ( $\pm 65.60$ ) Ab	100.00 ( $\pm 26.50$ ) ab	305.00 ( $\pm 36.20$ ) A	33.30 ( $\pm 1.70$ ) a	330.00 ( $\pm 31.80$ ) A	43.30 ( $\pm 7.30$ ) a
PHCTA	691.70 ( $\pm 164.70$ ) A	33.30 ( $\pm 1.70$ ) a	188.30 ( $\pm 21.70$ ) B	45.00 ( $\pm 2.90$ ) a	208.30 ( $\pm 15.90$ ) B	63.30 ( $\pm 1.70$ ) b
TRFAL	156.70 ( $\pm 26.20$ ) B	150.00 ( $\pm 41.90$ ) bc	188.30 ( $\pm 4.40$ ) B	35.00 ( $\pm 2.90$ ) a	95.00 ( $\pm 14.40$ ) B	88.30 ( $\pm 4.40$ ) c
VICSA + TTLRI	370.00 ( $\pm 55.00$ ) B	103.30 ( $\pm 17.40$ ) ab	326.70 ( $\pm 6.00$ ) A	33.30 ( $\pm 1.70$ ) a	418.30 ( $\pm 62.10$ ) A	45.00 ( $\pm 5.80$ ) a
WEEDS (Control)	-	205.00 ( $\pm 14.40$ ) c	-	85.00 ( $\pm 7.60$ ) b	-	185.00 ( $\pm 2.90$ ) d
	df = 11 F = 5.522 p = 0.024	df = 14 F = 6.855 p = 0.006	df = 11 F = 11.993 p = 0.002	df = 14 F = 30.466 p = 0.000	df = 11 F = 14.989 p = 0.001	df = 14 F = 148.036 p = 0.000

\* The average means of letters are different from each other at the  $p < 0.05$  level of statistical significance, according to Duncan's Multiple Comparison Test

The cover crops and weeds within the frame were, then, harvested, and their dry biomass were recorded. As displayed in Table 5, with the limited irrigation, the highest dry biomass of cover crops was obtained from LTHSA and VICSA + TTLRI in all of the years except the first year, when PHCTA showed the highest biomass ( $691.70 \text{ g m}^{-2}$ ); specifically, in the second and third years, LTHSA ( $305.00$ ;  $330.00 \text{ g m}^{-2}$ ) and VICSA + TTLRI ( $326.70$ ;  $418.30 \text{ g m}^{-2}$ ) were grouped together and were holding the highest biomass.

The weed dry biomass decreased as cover crop dry biomass increased: the more significant the cover crop biomass was, the lower the weed biomass was. In the PHCTA plots, the weed biomass was  $33.30 \text{ g m}^{-2}$  in 2021. Despite being in the same group for the cover crop plots (due to abundant rainfall) in 2022, the most significant effects were observed in LTHSA and VICSA + TTLRI ( $33.30 \text{ g m}^{-2}$ ). In 2023, the most significant impact was observed in the LTHSA ( $43.30 \text{ g m}^{-2}$ ) and VICSA + TTLRI ( $45.00 \text{ g m}^{-2}$ ) plots. Throughout the experiment, the highest weed biomass was obtained from the weedy control plots ( $85.00$ – $205.00 \text{ g m}^{-2}$ ) (Table 5).

## Discussion

The findings of the study are consistent with previously reported findings in that water scarcity in conjunction with drought in the Mediterranean region (where vineyard cultivation is important) might lead to problems in the development of viticulture (Saayman & Van Huyssteen, 1983; Lopes et al., 2008, 2011; Yang et al., 2022). Furthermore, the restriction

on herbicide use according to the regulations of the European Green Deal has led to a search for alternative weed control options in vineyards (Guerra et al., 2022a; Cabrera-Pérez et al., 2022; Muñoz et al., 2022). In addition to the importance and reduction of water use (Bernardo et al., 2018; Raza et al., 2019), studies conducted in both Türkiye and other countries have commonly examined the use of cover crops to reduce herbicide use (Kaçan & Boz, 2015; Tursun et al., 2018; Demir & Işık, 2020; Hall et al., 2020; Guerra et al., 2022a). In some studies conducted in South Africa, Spain, and Portugal, the use of cover crops against weeds has been observed in vineyards with limited irrigation (Saayman & Van Huyssteen, 1983; Van Huyssteen et al., 1984; Lopes et al., 2008; Guerra et al., 2022b; Candiago et al., 2023).

Considering the European Green Deal and its implications for the global climate, we investigated the usage of cover crops as an alternative to herbicide in Mediterranean vineyards and limited water application in this study. The effects of cover crops (LTHSA, PHCTA, TRFAL, and VICSA + TTLRI) were observed in the experimental plots during the winter and spring seasons from 2020 to 2023, and 24 different weed species were recorded during the observation periods during which *Veronica arvensis* L., *Fumaria officinalis* L., and *Avena sterilis* L. were the dominant species (Table 3). Our findings seemed to be consistent with weed species found in vineyards in Aegean region of Türkiye and in vineyard trial areas in Spain and Portugal (Lopes et al., 2008, 2011; Cabrera-Pérez et al., 2022; Guerra et al., 2022b).

In addition, when the cover crop–weed competition criteria was taken into consideration, we observed that VICSA + TTLRI and LTHSA had the highest coverage

area, and that they also sustained the lowest weed coverage throughout the observation period, (Fig. 1). Studies have shown that the specific growth characteristics of a cash crop can prevent weed competition, and cover crops with rapid and wide growth habits can effectively compete with weeds (Krishnamurthy et al., 1981; Place et al., 2011; Rasmussen et al., 2021). However, it was noted in this study that cover crop height only had a significant effect on weed suppression in the first observation period (80 DAS) (Fig. 2). On the other hand, proliferative cover crops with narrow leaves that do not have substantial covering capacity during their development may sometimes not provide adequate weed control in agricultural systems (Jarvis-Shean, 2019). The results of the current study suggest that cover crop height may not be the primary factor affecting weed suppression; instead, cover crops' fast development and extensive canopy contribute to the reduction of weed growth by shading the soil surface and (out-)competing for light, water, and nutrients as reported in the related study (Blackshaw et al., 2001).

Furthermore, the results of the experiment found clear support for the length of light exposure in that cover crops prevented weed exposure to light and shared shading with weeds. In general, all cover crops were in the same group in terms of shading except for the first observation period (80 DAS), with the control plots having the highest values (Fig. 3). VICSA+TTLRI was found to be the dominant cover crop in terms of weed coverage, followed by LTHSA and PHCTA (Fig. 4). The extensive growth, branches, and leaves of the cover crops significantly increased the shade on the soil surface. Therefore, longer light exposure resulted in greater shading by the cover crops, which contributed to weed suppression. Considering the findings, we suggest that VICSA+TTLRI, LTHSA, and PHCTA can effectively suppress weed growth and are suitable for use in vineyards with limited water application.

During the first and second years, VICSA+TTLRI and PHCTA effectively reduced weed density, but in the last year, only VICSA+TTLRI effectively reduced weed numbers. The highest weed densities were obtained from the control plots. The dry biomass of the cover crops VICSA+TTLRI, LTHSA, and PHCTA were the highest, in which causing the lowest weed dry biomass (Table 5). The results confirmed that the prominent cover crops effectively suppressed weed density

and positively affected the growth of vines. It has been stated in previous studies that in general, cover crops should compete with weeds and demonstrate good efficacy in reducing the weed species, density, and biomass (Bradshaw & Lanini, 1995; Kolören & Uygur, 2006; Linares et al., 2008; Isik et al., 2013; Tursun et al., 2018; Doll, 2019). It has also been suggested that the design and adaptation of a specific cover crop in relation to weed management, characteristic properties, regional climate differences, and geographical and ecological conditions should be comprehensively evaluated (Zhou et al., 2014), because agricultural systems need reliable and highly effective weed management strategies based on ecological approaches.

## Conclusions

The aim of this study was to assess the effectiveness of the cover crop species in weed management and their potential contribution to integrated weed management strategies. The findings revealed that cover crops can be an effective alternative way for managing water scarcity and drought in vineyard cultivation. In addition, the findings imply that cover crops can play a significant role in weed control, and thus contribute to the sustainable productivity of vineyards. The findings also suggest that the selection of a cover crop should be associated with the regional specificities and environmental conditions. We conclude that the cover crops VICSA+TTLRI, LTHSA, and PHCTA can easily be used in vineyards with limited water application, as they contribute to enhancing biodiversity in vineyards and help them maintain productivity for longer by improving their water retention capacity during dry conditions since cover crops are expected to be globally beneficial in vineyards, where perennial monoculture is practiced (Jannoyer et al., 2011; Lavigne et al., 2012).

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**Data availability** All data relevant to this study is provided within the manuscript.

## Declarations

**Competing interests** The authors declare no competing interests.

**Conflict of interest** The authors declare that there are no conflicts of interest related to this article.

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