Gesunde Pflanzen (2022) 74:317–332
https://doi.org/10.1007/s10343-021-00611-0

ORIGINAL ARTICLE / ORIGINALBEITRAG

Impact of Irrigation Timing and Weed Management Practices on Chlorophyll Content and Morphological Traits of Tomato (*Solanum lycopersicum* Mill.)

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Received: 1 October 2021 / Accepted: 7 December 2021 / Published online: 6 January 2022

Abstract

Weeds are a major biotic constraint; compete with crop for the same resources and ultimately reduce productivity. This study evaluated the impact of irrigation intervals and weed management treatments on chlorophyll content and morphological growth of tomato to find an appropriate integrated weed management strategy. Two-year field experiments (2018/2019) were conducted at district Mardan (34°15′38″ N and 72°6′36″ E). Tomato F1 hybrid (Taj-3592) was transplanted during March. The experiments were laid out in a randomized complete-block design in split-plot arrangement with three replications. The main block comprised three irrigation intervals (3, 6, and 9 days) and the sub-block included weed management treatments: transparent polythene, black polythene, weeding except *Orobanche*, sole weeding of *Orobanche*, weeding of all weeds, copper oxychloride 1.5 kg a.i ha^{-1} (single dose), copper oxychloride 1.5 kg a.i ha^{-1} (split doses), copper oxychloride + humic acid 25 kg ha^{-1} (single dose), copper oxychloride + humic acid 25 kg ha^{-1} (split doses), copper sulphate 2 kg ha^{-1} (single dose), copper sulphate 2 kg ha^{-1} (split doses), ammonium sulphate 200 kg ha^{-1} (single dose), ammonium sulphate 200 kg ha^{-1} (split doses), pendimethalin 33 EC 1.44 kg a.i ha^{-1}, glyphosate 48 SL 1.5 kg a.i ha^{-1}, and weedy check. Lowest relative weed density (RWD) of *O. cernua* (2.23%) and highest RWD of *O. cernua* (38.01%) were recorded in the 3- and 9-day irrigation intervals, respectively. However, 3-day irrigation interval resulted in highest fresh weed biomass (5794 kg ha^{-1}). Moreover, the 6-day irrigation interval significantly increased chlorophyll content by 11 and 5%, leaf area by 23 and 6%, and number of branches $plant^{-1}$ by 30 and 22% compared to 9- and 3-day irrigation intervals, respectively. Among the weed management treatments, black polythene resulted in the highest weed control efficiency (96%), increasing chlorophyll content by 16%, leaf area by 33%, and number of branches $plant^{-1}$ by 64% vs. weedy check. Consequently, 6-day irrigation intervals × black polythene could be the best weed management strategy, followed by transparent polythene, weeding of all weeds, pendimethalin, glyphosate, and ammonium sulphate.

Keywords Integrated weed management · Irrigation intervals · Weed control efficiency · Broomrape · Black plastic mulch

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Auswirkung des Bewässerungszeitpunkts und der Unkrautbekämpfungsmaßnahmen auf den Chlorophyllgehalt und die morphologischen Eigenschaften der Tomate (*Solanum lycopersicum* Mill.)

Zusammenfassung

Unkräuter sind die größte biotische Einschränkung, die mit den Pflanzen um dieselben Ressourcen konkurrieren und letztlich die Produktivität der Pflanzen verringern. Ziel dieser Studie war es, die Auswirkungen von Bewässerungsintervallen und Unkrautbekämpfungsmaßnahmen auf den Chlorophyllgehalt und das morphologische Wachstum von Tomaten zu bewerten und eine geeignete integrierte Unkrautbekämpfungsstrategie zu finden. In den Jahren 2018 und 2019 wurden 2-jährige Feldversuche im Distrikt Mardan (34°15′38″ N und 72°6′36″ O) durchgeführt. Die determinierte Tomate-F1-Hybride (Taj-3592) wurde im März gepflanzt. Die Versuche wurden in einem randomisierten vollständigen Blockversuch (RCBD) mit geteilter Parzellenanordnung und 3 Wiederholungen angelegt. Der Hauptblock bestand aus 3 Bewässerungsintervallen (3, 6 und 9 Tage), während der Unterblock Unkrautbekämpfungsbehandlungen enthielt, nämlich durchsichtige Polyethylenfolie, schwarze Polyethylenfolie, Jäten aller Unkräuter mit Ausnahme von *Orobanche*, alleiniges Jäten von *Orobanche*, Jäten aller Unkräuter, Kupferoxychlorid 1,5 kg a.i ha^{-1} (Einzeldosis), Kupferoxychlorid 1,5 kg a.i ha^{-1} (Split-Dosis), Kupferoxychlorid + Huminsäure 25 kg ha^{-1} (Einzeldosis), Kupferoxychlorid + Huminsäure 25 kg ha^{-1} (Split-Dosis), Kupfersulfat 2 kg ha^{-1} (Einzeldosis), Kupfersulfat 2 kg ha^{-1} (Split-Dosis), Ammoniumsulfat 200 kg ha^{-1} (Einzeldosis), Ammoniumsulfat 200 kg ha^{-1} (Split-Dosis), Pendimethalin 33 EC 1,44 kg a.i ha^{-1}, Glyphosat 48 SL 1,5 kg a.i ha^{-1} und Unkrautkontrolle. Unter den Bewässerungsintervallen wurde die niedrigste (2,23 %) und die höchste (38,01 %) relative Unkrautdichte (RWD) von *Orobanche cernua* bei einem Bewässerungsintervall von 3 bzw. 9 Tagen festgestellt. Das Bewässerungsintervall von 3 Tagen führte jedoch zu der höchsten frischen Unkrautbiomasse (5794 kg ha^{-1}) im Vergleich zu den Bewässerungsintervallen von 6 und 9 Tagen. Darüber hinaus erhöhte ein Bewässerungsintervall von 6 Tagen den Chlorophyllgehalt um 11 % bzw. 5 %, die Blattfläche um 23 % bzw. 6 % und die Anzahl der Zweige pro Tomatenpflanze um 30 % bzw. 22 % im Vergleich zu einem Bewässerungsintervall von 9 bzw. 3 Tagen. Von den Behandlungen zur Unkrautbekämpfung führte die schwarze Polyethylenfolie zu der höchsten Effizienz bei der Unkrautbekämpfung (96 %) und erhöhte den Chlorophyllgehalt um 16 %, die Blattfläche um 33 % und die Anzahl der Zweige pro Pflanze um 64 % im Vergleich zur Unkrautkontrolle. Folglich könnten 6-tägige Bewässerungsintervalle × schwarze Polyethylenfolie gefolgt von transparenter Polyethylenfolie, Jäten aller Unkräuter, Pendimethalin, Glyphosat und Ammoniumsulfat die beste Unkrautbekämpfungsstrategie sein.

Schlüsselwörter Integrierte Unkrautbekämpfung · Bewässerungsstrategien · Effizienz der Unkrautbekämpfung · Chlorophyll · Ernte

Introduction

Tomato (*Solanum lycopersicum* Mill.) is an important nutritious fruit, commonly used as a vegetable or in combination with other vegetables. It is the second most important and widely consumed vegetable crop worldwide (Saleem et al. 2019). It is an extremely rich source of vitamins A, B, C, iron, potassium, and secondary metabolites with high antioxidant efficiency. The yellow-color tomato fruits are known for being an excellent source of vitamin A, while red-color tomato is rich in lycopene carotenoid—a potent antioxidant with excellent anti-aging properties. Tomato is an important source of bioactive compounds which prevent certain cancer and cardiovascular diseases (Zhang et al. 2015; Shah et al. 2021). It is widely consumed either raw or after processing and used as salad, cooked in soup, with meat, and also for making sauces and ketchup.

Tomato production is obstructed by various biotic factors, i.e., weeds, insects/pest, pathogens, etc. Weeds compete with the crop for water, light, space, and nutrients, and ultimately reduce crop productivity. Among all pests, parasitic weeds are one of the major biotic constraints which greatly reduce tomato growth (Fernandez-Aparicio et al. 2016). Broomrape is a major root-parasitic weed of tomato, which is hard to control due to the intimate underground association of the parasite haustoria with the roots of the host plant (Goldwasser et al. 2021). Unlike other weeds, broomrape directly drains water and nutrients from the host plant and completely damages it. Broomrape (*Orobanche* spp.) belongs to the Orobanchaceae family in the dicot group of angiosperms. The genus *Orobanche* has more than 150 species that pose a severe threat to economically important crops globally (Nosratti et al. 2020). Branched broomrape (*O. ramosa*) and Egyptian broomrape (*O. aegyptiaca*) have invaded about 2.6 million hectares of solanaceous crops in the North African, Asian, and Mediterranean region. Broomrape species are estimated to cause about USD 1.3 to 2.6 billion of economic losses globally in vegetables crops (Joel 2013). Broomrape species are more destructive and drastically reduce tomato yield in Pakistan (Ahmad et al. 2018).

The *Orobanche* incidence in Pakistan is increased due to monocropping culture of Solanaceae crops, particularly tobacco and tomato crop, which are among the crops most susceptible to infection by broomrape. Broomrape seeds are tiny in nature, with long-term seed viability and an outstanding dispersal mechanism which is hard to control. Efficient management of these weeds is challenging due to their complicated and parasitic nature (Nosratti et al. 2020). Many management plans have been tried; only few of them have proved reliable and economical. Numerous techniques, such as use of trap crop, crop rotation, herbicides, drip irrigation, nitrogen fertilizers, solarization, flooding, and frequent irrigation effectively reduce the *Orobanche* seed bank and its severity (Das et al. 2020). However, there is no single method that can completely eradicate *Orobanche* infestation. Weed scientists have used integration of various weed control measures to suppress the *Orobanche* population. Broomrape attacks mostly solanaceous crops; hence, the cropping of tomato and tobacco in these regions leads to very high infestation of *O. cernua*, which severely reduces the yield and fruit quality of tomato.

Appropriate and timely weed management could be the best strategy to improve crop productivity. Various polythene mulches were used in this study to suppress weeds organically. Moreover, mulching soil with polythene sheets is a long-term weed management approach which could suppress weeds throughout the crop growing season. Additionally, mulching also increases microbial activity in the soil, prevents light from reaching the soil surface, and also conserves soil moisture. All these factors contribute to indirect weed control. The present study focusses on integrating the irrigation interval with weed control strategies to reduce weed infestation. Precise irrigation application to the crop can also alter the habitat to become unfavorable for some weeds, particularly broomrape (Baghla et al. 2020). The present study was designed to investigate the impact of irrigation intervals and weed management treatments on tomato leaf chlorophyll content and morphological attributes of tomato. The aim was to find an appropriate

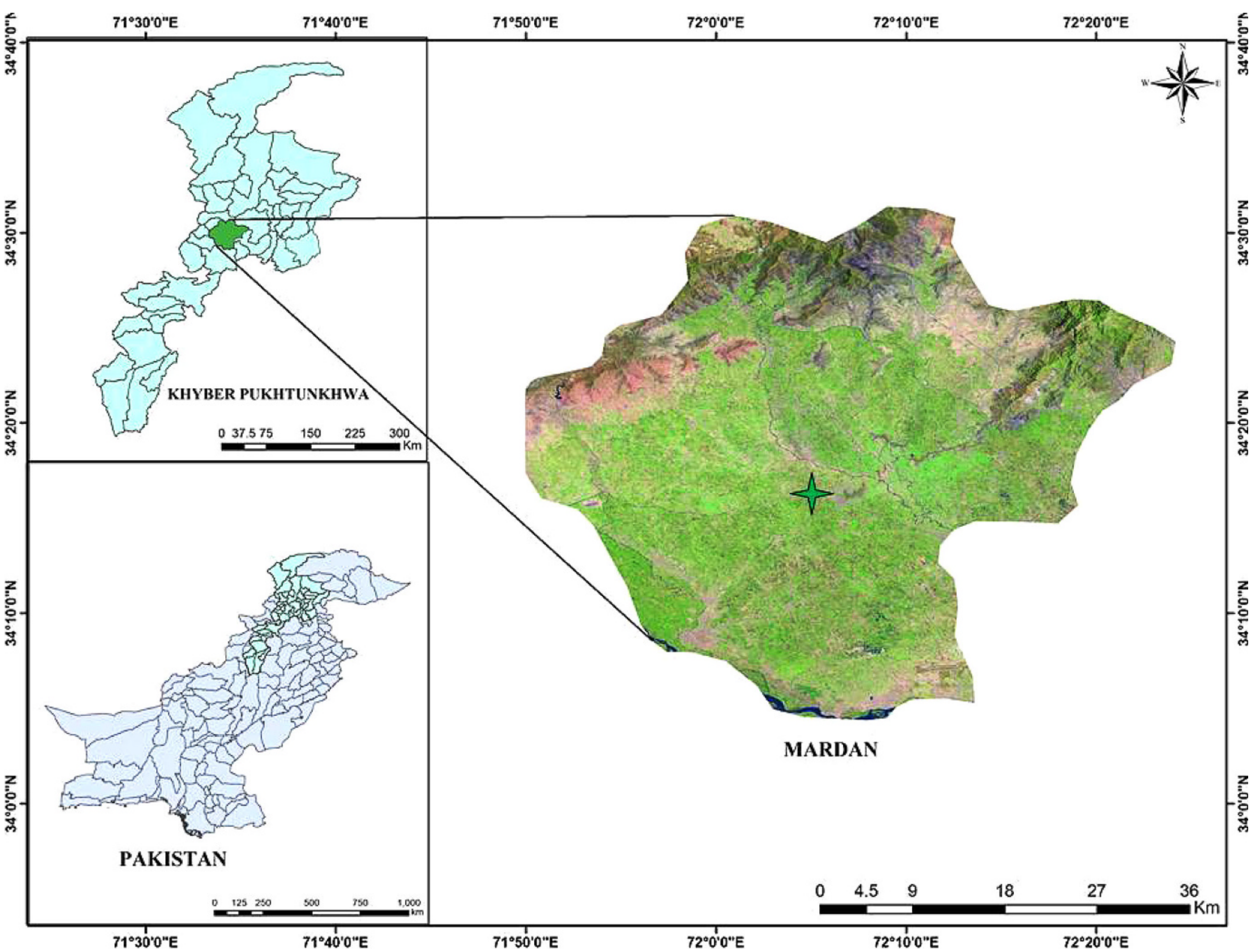


Fig. 1 Study area map

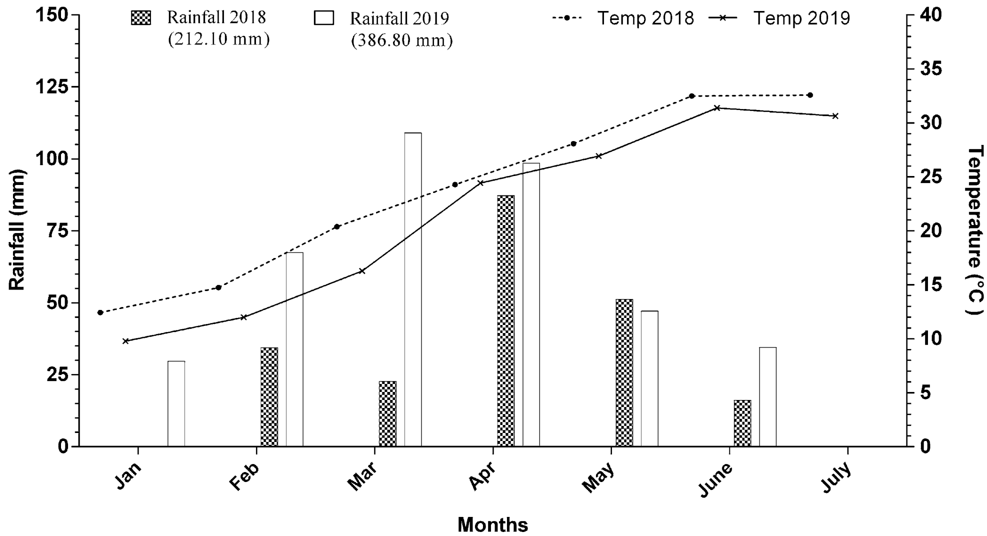


Fig. 2 Mean rainfall and temperature variation of the study area during the growing seasons (2018 and 2019)

and efficient weed management practice and to evaluate the impact of irrigation intervals on relative weed density and fresh weed biomass.

Materials and Methods

Experimental Site Description

This research was conducted as field experiments during 2018 and 2019. The experimental site was located in district Mardan (Khyber Pakhtunkhwa) Pakistan (34°15′38″ N, 72°6′36″ E), Fig. 1. The soil of the experimental field was silty clay loam in texture, alkaline in reaction (pH = 7.75), non-saline (EC = 0.45 dS m^{-1}), organic matter content (OM = 0.07%), poor in N (0.6%), with adequate available P (4.44 mg kg^{-1}) and high in K (120.2 mg kg^{-1}). The weather data during the 2018 and 2019 tomato growing seasons is presented in Fig. 2.

Experimental Setup

The experiment was conducted according to a split-plot design which was employed in a randomized complete-block design (RCBD) with three replications. Three irrigation timings (3-, 6-, and 9-day intervals) were the main plots, while treatments were allocated to the sub-plots and were repeated in the 2 years (year × irrigation time × treatments). The field was thoroughly plowed; leveled and raised beds of 4 × 12 feet were prepared. Tomato (*Solanum lycopersicum*) seeds at the rate 150 g were sowed for nursery raising. Tomato seedling F1 hybrid Taj-3592 was transplanted in March 2018. Distance between the replications was 90 cm and between the main plot and sub-plot was kept at 50 cm. Distance between the plants was 30 cm and between rows 90 cm. The crop was irrigated 1 week after transplantation (WAT) and irrigated thereafter at 3-, 6-, and 9-day intervals. Weed control treatments and black and transparent polythene were applied before seedling transplantation. The recommended dose of pendimethalin herbicide was applied pre-emergence to moist soil. The herbicide glyphosate was sprayed postemergence 4 and 8 weeks after transplantation (WAT). Glyphosate is a nonselective and systemic herbicide; therefore, it was sprayed selectively on weeds with a protective shield to avoid crop injury. Ammonium sulphate, humic acid, copper sulphate, and copper oxychloride were applied at 4 and 8 weeks after transplantation (WAT) in single and split doses, respectively. Hand weeding was practiced at 4 and 8 WAT.

Data Collection and Measurements

Relative Weed Density (m^{-2})

Data on relative weed density were recorded in each main plot using the following equation (Holm et al. 1977).

$$Relative\,weed\,density\,\% = \frac{Mean\,of\,\,individual\,specie}{Mean\,of\,\,total\,species} \times 100 \tag{1}$$

Fresh Weed Biomass (kg ha^{-1})

Data on fresh weed biomass were recorded after 1 month of treatment application. The fresh biomass of all the weeds was collected by applying three random quadrates (50 × 50 cm) in each sub-plot and then computing mean fresh weed biomass. Subsequently, the data were converted into kg ha^{-1}.

Weed Control Efficiency (WCE%)

Weed control efficiency (WCE) indicates the efficacy of weed control treatments. The weed control efficiency of treatment was calculated for all the sub-plots using the following equation (Gill and Kumar 1969; Chaudhari et al. 2019).

$$\text{Weed control efficiency } \% = \frac{\text{DWC} - \text{DWT}}{\text{DWC}} \times 100 \quad (2)$$

DWC= Dry weight of weeds in weedy check
DWT= Dry weight of weeds in treated plots

Number of Branches Plant^{-1} of Tomato

Data on the number of branches plant^{-1} were recorded randomly from five tagged plants in each sub-plot at plant maturity, and the average number of branches plant^{-1} was then computed.

Leaf Area (cm^2) Plant^{-1} of Tomato

Leaves were collected randomly from five selected plants in both the main plot and the sub-plot during the end of the fruiting stage. Leaf area (cm^2) was measured using a leaf area meter.

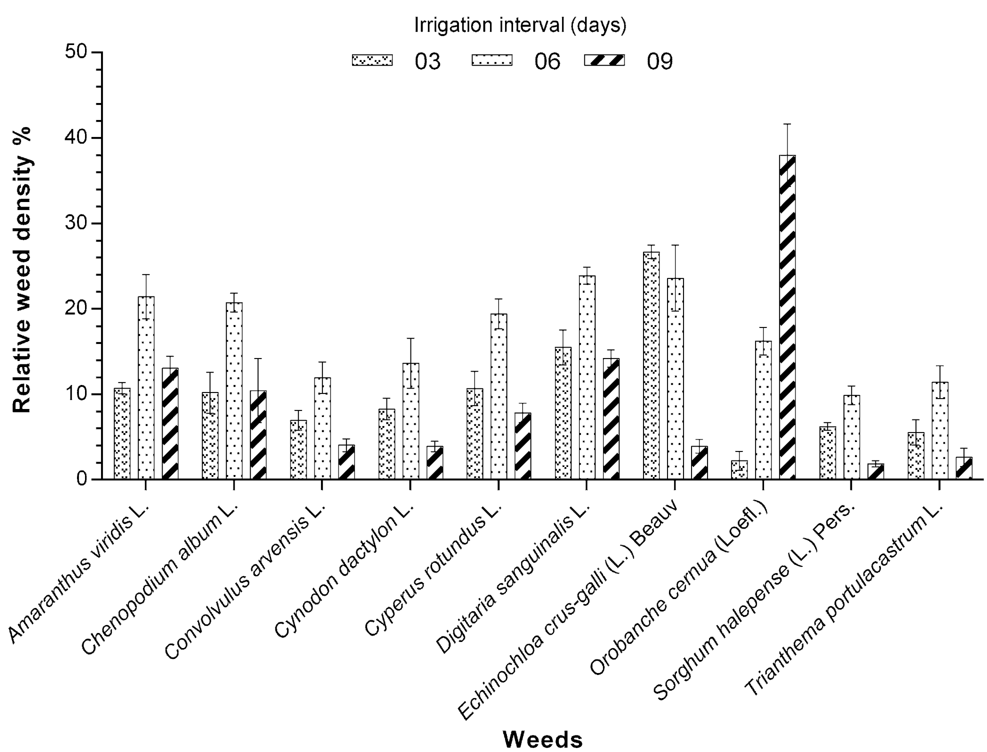
Chlorophyll Content (SPAD) Plant^{-1} of Tomato

Chlorophyll content was determined using a soil plant analysis development (SPAD) meter (Konica Minolta SPAD-502 plus; Marunouchi, Chiyoda, Tokyo, Japan). This instrument estimates the nutritional status of the tomato plants (Yang et al. 2014). The chlorophyll content of parasitized tomato plants in each treatment was recorded at 55 days after transplantation (DAT). This is a nondestructive measurement of leaf chlorophyll concentration.

Statistical Analysis

The data for individual traits were statistically analyzed by analysis of variance (ANOVA) techniques using the Statistix 8.1 package (Analytical Software, Tallahassee, FL, USA). Wherever, the F-value was found significant, the least significant differences (LSD) test was carried out at the 5% level of probability to establish differences among various treatments as outlined by Steel and Torrie (1980). All the mean and interaction data were converted into line and bar graphs using GraphPad Prism 6 software (GraphPad Software Inc., San Diego, CA, USA).

Fig. 3 Effect of various irrigation intervals on relative weed density ± standard error



Results and Discussion

Relative Weed Density

The data shown in Fig. 3 represent the impact of irrigation regimes on relative weed density in tomato field. The data show that a 9-day irrigation interval resulted in the highest RWD of 38.01% for *Orobanche*, followed by the 6- and 3-day irrigation intervals with a RWD of 16.24 and 2.23%, respectively, while the minimum RWD was recorded for *Sorghum halepense* (1.88%), *Cynodon dactylon* (3.92%), and *Echinochloa crus-galli* (3.93%) in the 9-day irrigation interval (Fig. 3). Similarly, the lowest RWD was recorded for *Orobanche cernua* (2.23%) in the 3-day irrigation interval. Likewise, the highest RWDs were recorded for *E. crus-galli* (23.61%) and *Digitaria sanguinalis* (15.5%) in the 3-day irrigation interval. This variation in weed composition in response to various irrigation intervals might be due to the fact that weeds belong to different families with different life forms, physiology, and water requirements. The data further show that *E. crusgalli* is relatively hydrophilic in nature and grows in well-irrigated conditions. Similarly, *O. cernua* is quite hydrophobic in nature and cannot tolerate frequent irrigation (3-day irrigation interval). Consequently, increased irrigation intervals decreased the RWD of hydrophilic weeds, particularly *E. crus-galli*, and increased the RWD of hydrophobic weeds, particularly *O. cernua*. Moreover, *Orobanche* management should be prioritized because of its direct attachment to the host plant, which alone causes huge yield losses compared to all other weeds of tomato. *Orobanche* has a direct connection with tomato roots, thereby absorbing water and nutrients directly from the host plant. This results in a significant decline in crop growth and ultimately causes death of the crop. Therefore, optimizing the irrigation interval could be a unique cultural, ecofriendly, and novel practice to suppress *Orobanche* spp. instead of using costly and hazardous herbicides.

Broomrape is comparatively susceptible to flooding or frequent irrigation and did not survive an extended period of inundation (Rashed et al. 2001). Similarly, Karkanis et al. (2007) also reported that irrigation throughout the growing season significantly reduced *Orobanche* infestation. Moreover, drip irrigation reduces *Orobanche* infestation by 70–76%. Previous research suggested that *Orobanche* seeds are susceptible to flooding and frequent irrigation, which decreases germination vigor considerably as well as attachment to the host plant (Punia 2014). Therefore, frequent and light irrigation throughout the growing season could maintain the soil moist, where the stem and the haustorium of *Orobanche* become rotten and completely damaged. The rotten *Orobanche* stem might be due to excessive moist soil that might provide an appropriate medium for soil-

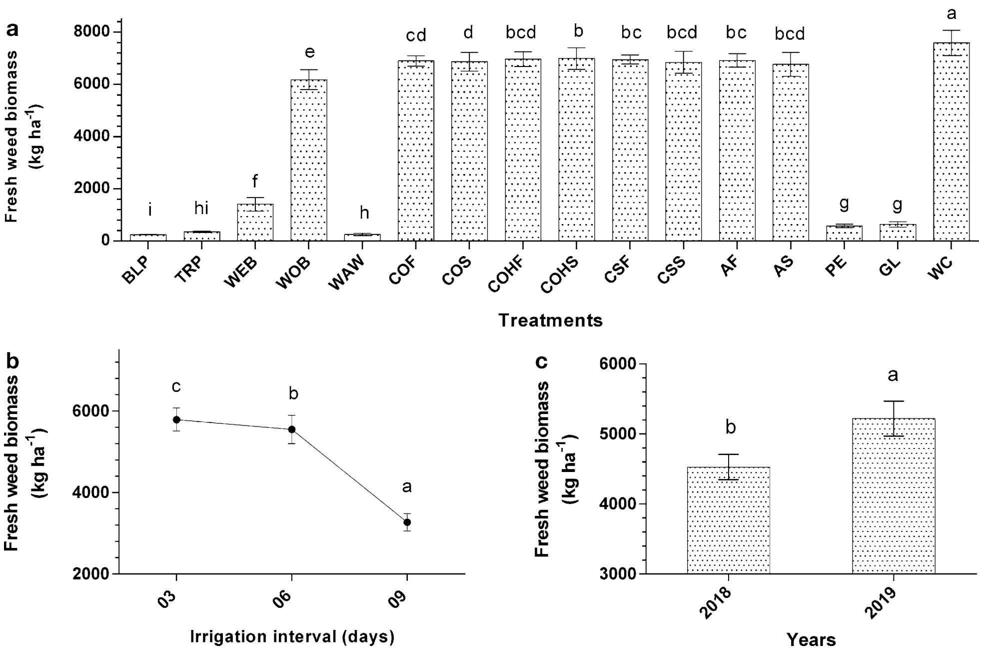


Fig. 4 Effect of irrigation intervals and weed control treatments on weed fresh biomass (kg ha^{-1}). Based on least significant difference test, *lines* and *columns* ± standard error followed by different alphabetical *letters* are significantly different from each other at the 5% level. **a** Effect of weed management treatments on fresh weeds biomass (kg ha^{-1}). **b** Effect of irrigation intervals on fresh weeds biomass (kg ha^{-1}). **c** Effect of years on fresh weeds biomass (kg ha^{-1}). *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

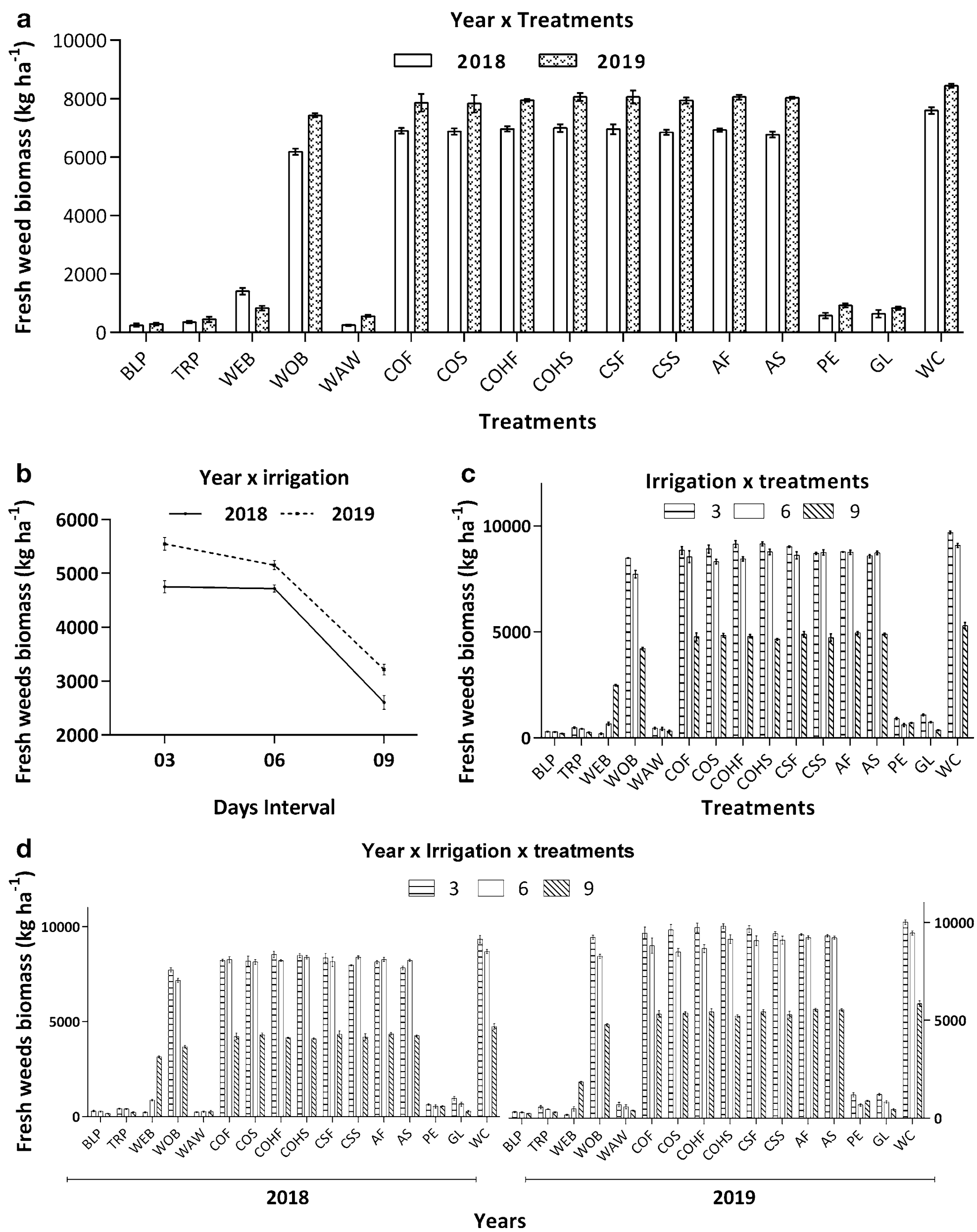


Fig. 5 Interaction for year × treatments (**a**), year × irrigation (**b**), and irrigation × treatments (**c**) year × irrigation × treatments (**d**) on fresh weed biomass (kg ha^{-1}). *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

beneficial microbes which particularly attack *Orobanche* and completely damage it. Previous research reports have confirmed that the fungus species *Fusarium oxysporum* causes root rot in the Orobanchaceae family but does not attack crops (Mehrabi 1997; Ershad 2009; Esk et al. 2012). Hence, our 2-year studies lead to the conclusion that *O. cernua* is susceptible to frequent irrigation practices.

Fresh Weed Biomass

The results in Fig. 4 show that various irrigation intervals and weed management treatments significantly ($P \leq 0.05$) affect the fresh weed biomass. The combined-year ANOVA shows that fresh weed biomass (kg ha^{-1}) varied significantly during the years 2018 and 2019. The highest biomass of 4582.18 kg ha^{-1} was recorded during 2019 and the lowest weed biomass of 4018.13 kg ha^{-1} was recorded during 2018. Similarly, the interaction among year × treatments (a), year × irrigation (b), irrigation × treatments (c), and year × irrigation × treatments (d) was also found to be significant (Fig. 5). Apparently, variation in the weed fresh biomass (kg ha^{-1}) during the years and the significant interactions could be due to variation in the rainfall pattern.

Among the irrigation intervals, 3- and 6-day irrigation intervals resulted in the highest fresh weed biomass of 5794.73 and 5552.52 kg ha^{-1}, respectively, and the 9-day irrigation interval obtained the lowest weed biomass of

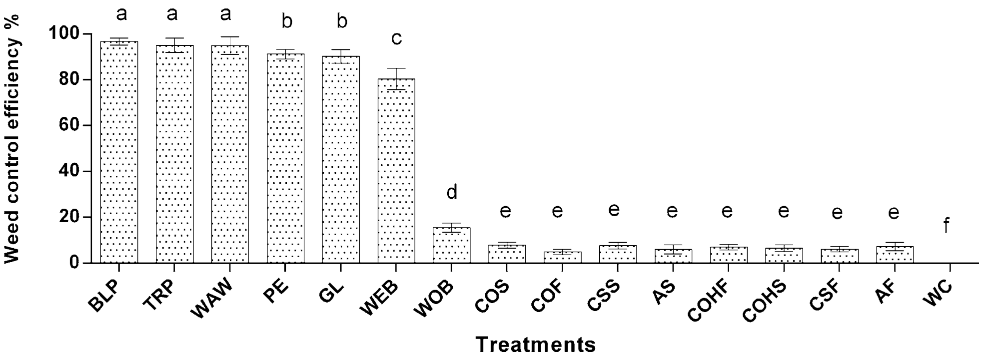
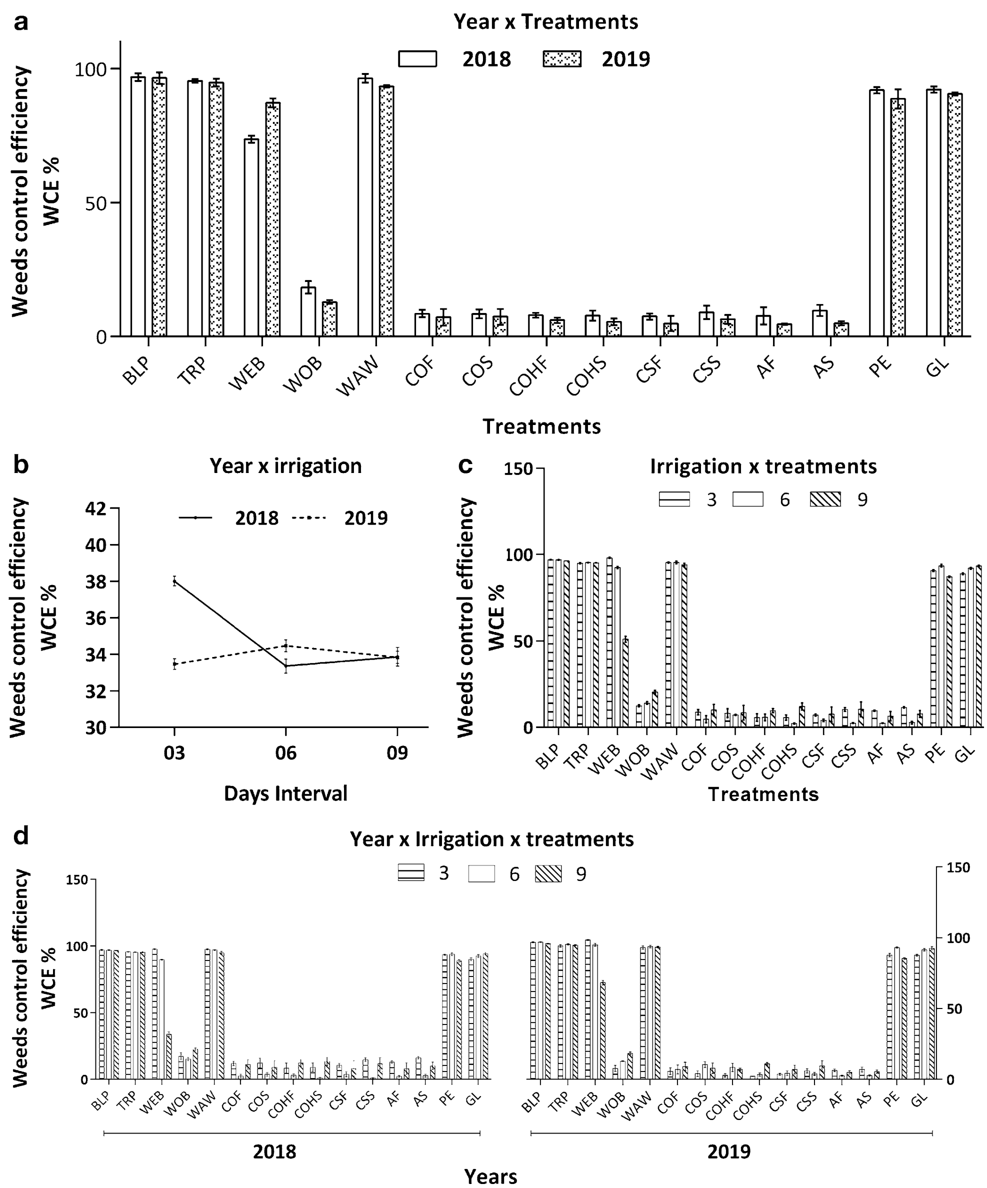


Fig. 6 Weed control efficiency of various weed management treatments. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COS* copper oxychloride (single dose) 2 kg ha^{-1}, *COF* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

Fig. 7 Interaction of year × treatments (**a**), year × irrigation (**b**), irrigation × treatments (**c**), and year × irrigation × treatments (**d**) on weed control efficiency (*WCE%*). *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose), 2 kg ha^{-1} *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)



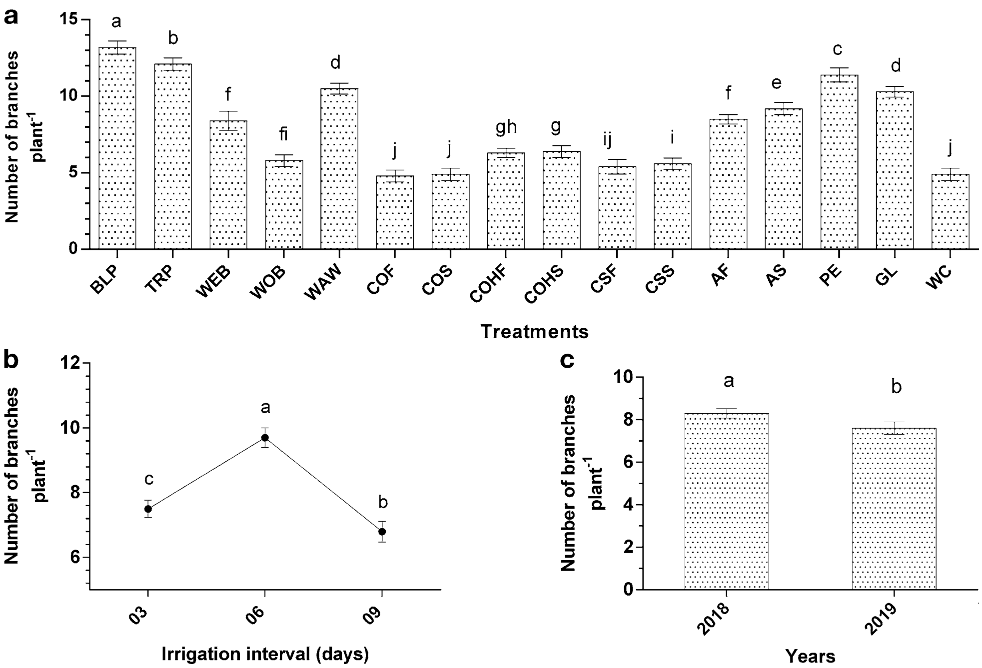


Fig. 8 Effect of various irrigation intervals and weed management treatments on the number of branches plant^{-1} of tomato. **a** Effect of weed management treatments on number of branches plant-1 of tomato. **b** Effect of irrigation intervals on number of branches plant-1 of tomato. **c** Effect of years on number of branches plant-1 of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

3272.64 kg ha^{-1}. Interestingly, weeds are persistent in nature and can tolerate either increased or decreased irrigation intervals. Moreover, the weed fresh biomass increased linearly with decreasing irrigation intervals. These results are in line with those of Gholamhoseini et al. (2013), who reported that a decrease in irrigation interval considerably increased fresh weed biomass.

Among the treatments, black and transparent polythene resulted lowest fresh weed biomass of 265.35 and 397.97 kg ha^{-1}, respectively, followed by weeding of all weeds (43.91 kg ha^{-1}) whereas, the highest fresh weeds biomass (8015.05 kg ha^{-1}) was obtained from the weedy check. Weed biomass has an inverse relation to crop biomass: an increase in weed biomass significantly decreases the crop biomass. Moreover, 1 kg of weed biomass will directly correspond to a 1-kg reduction in crop biomass (Rao 2000; Bakht 2015). Moreover, black polythene mulch was found to be effective against weeds and resulted in the lowest weed biomass. This could be attributed to the fact that black polythene increased the under-soil temperature and helped in suppressing the weed population as compared to the weedy check. These results are in conformity with those obtained by Kumar et al. (2019) and Boutagayout et al. (2020).

Weed Control Efficiency

The results in Fig. 6 indicate that various treatments significantly ($P \leq 0.05$) affect the percent weed control efficiency; however, the effect of irrigation intervals was nonsignificant. Combined-year analysis showed that weed control efficiency was nonsignificant; however, the interaction of year × treatments (a), year × irrigation (b), irrigation × treatments (c), and year × irrigation × treatments (d) was found to be significant (Fig. 7). In fact, the significant interaction could be due to variation in the weather pattern during the years, which might affect the efficacy of treatments. Additionally, the highest weed control efficiency and highest chlorophyll (SPAD) resulted for the 6-day irrigation interval × black polythene, followed by transparent polythene and pendimethalin. Hence, optimizing the 6-day irrigation interval together with polythene mulches could be suggested as the best integrated weed management strategy.

The data show that black polythene, transparent polythene, and weeding of all weeds resulted in the highest weed control efficiencies of 96.7, 95.1, and 94.9%, respectively, as compared to controls, which were statistically comparable. Apparently, the black polythene prevents sunlight penetrating and thereby increases the under-soil temperature and thus hinders weed germination. Furthermore, polythene

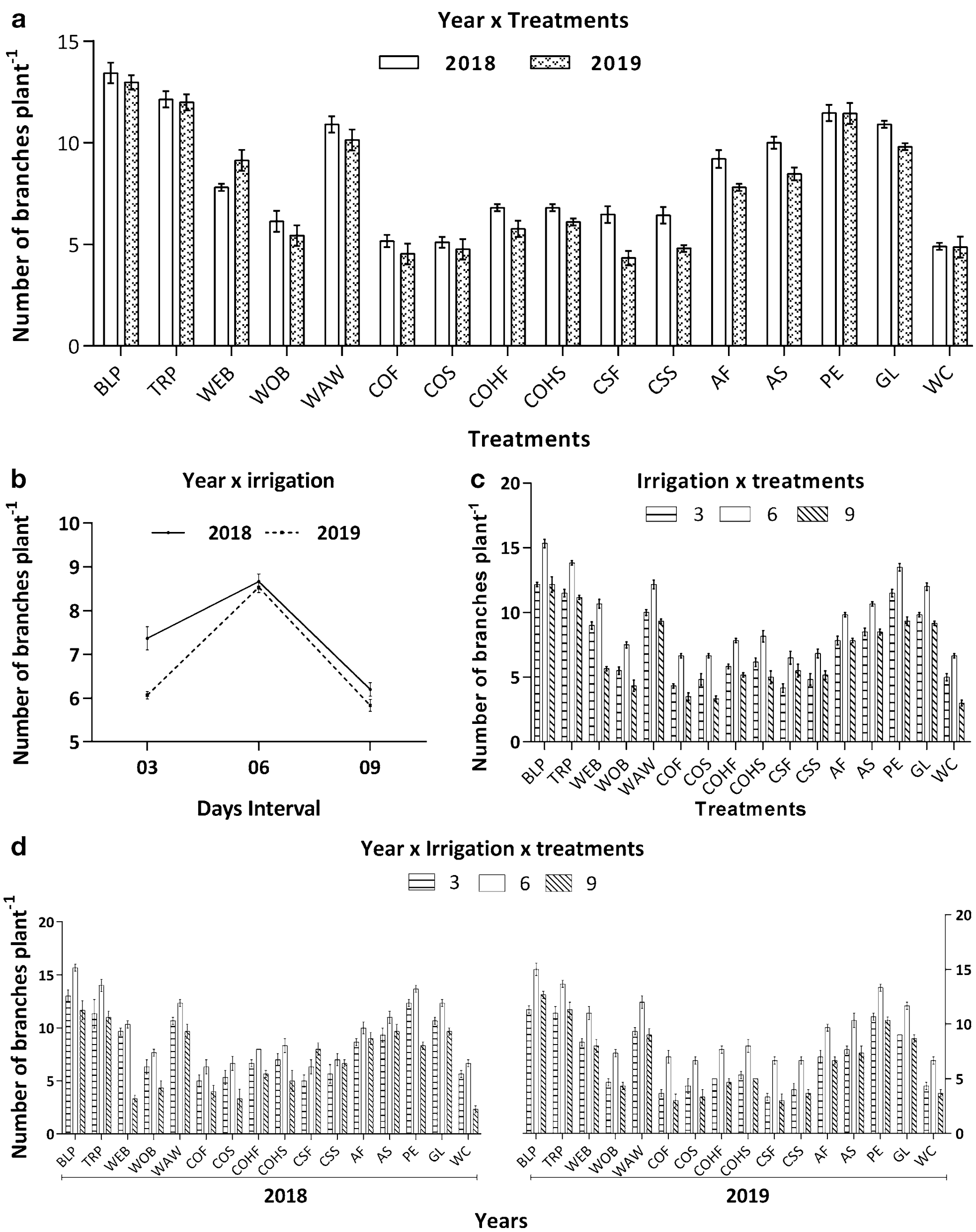


Fig. 9 Interaction of year × treatments (**a**), year × irrigation (**b**), irrigation × treatments (**c**), and year × Irrigation × treatments (**d**) on number of branches plant^{-1} of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

mulches suppress weeds throughout the tomato growing season and thus have the highest weed control efficiency. Moreover, previous findings evidenced that black polythene reduces weed density m^{-2} and could be an effective weed control practice (Nwosisi et al. 2019; Mishra et al. 2020). Furthermore, solarization using black polythene seems to be an effective weed management approach in tomato grown in raised beds compared to the plants grown on flat beds (Shukla et al. 2020). Thus, black polythene mulch could be encouraged for weed control in tomato.

Number of Branches Plant^{-1} of Tomato

The results presented in Fig. 8 show that irrigation interval and treatment significantly ($P \leq 0.05$) affected the number of branches plant^{-1}. Combined ANOVA showed that years has a significant effect on the number of branches plant^{-1} of tomato, where the maximum number of branches plant^{-1} of 10.60 was recorded during 2019 while the minimum of 9.68 was recorded during 2018. Similarly, the interaction among year × treatments (a), year × irrigation (b), irrigation × treatments (c), and year × irrigation × treatments (d) was also significant (Fig. 9). Apparently, the significant interactions and year data could be due to variation in the rainfall pattern and fluctuations in temperature that might

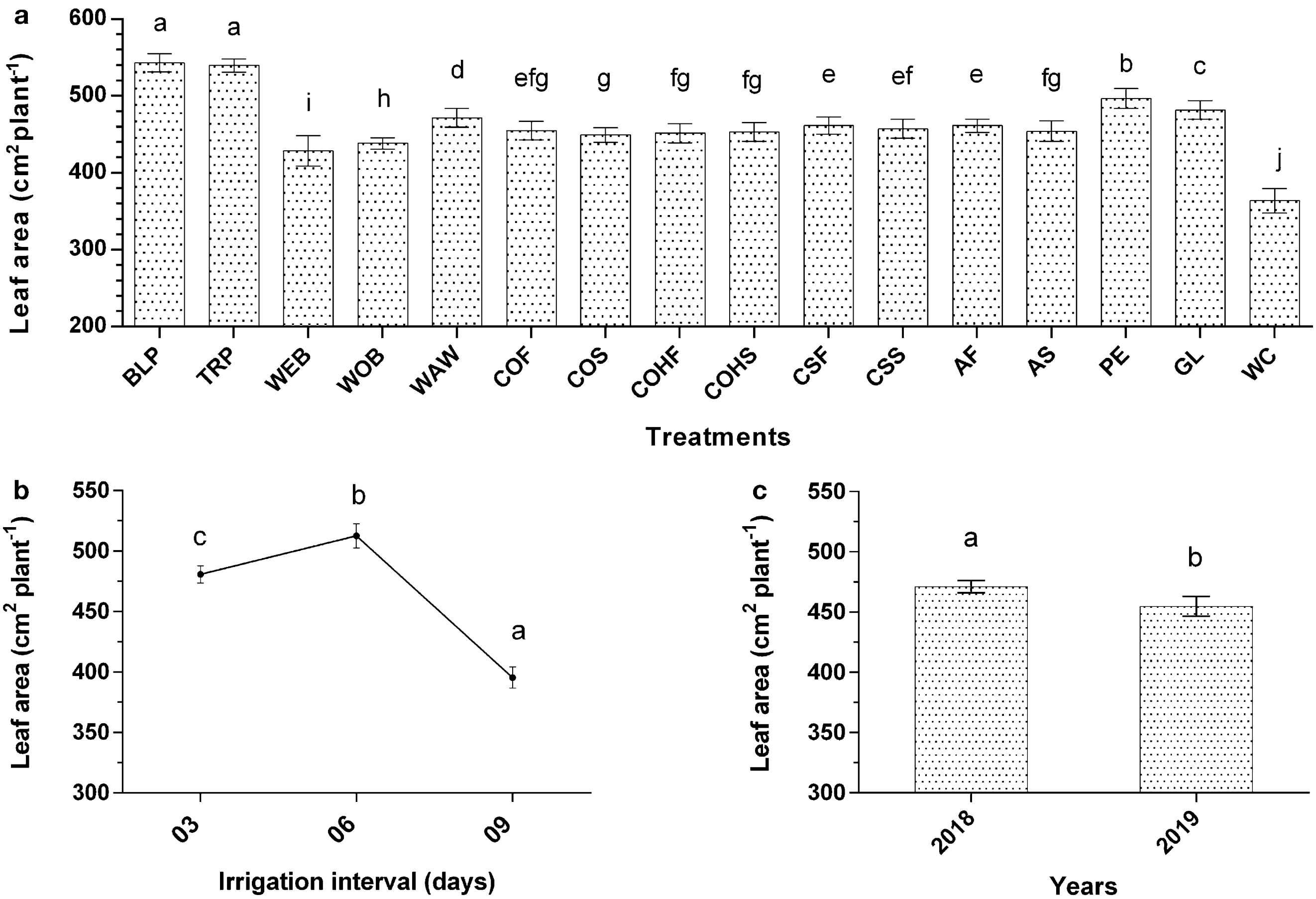


Fig. 10 Effect of irrigation intervals and weed control treatments on leaf area (cm^2) plant^{-1} of tomato. **a** Effect of weed management treatments on leaf area of tomato. **b** Effect of irrigation intervals on leaf area of tomato. **c** Effect of years on leaf area of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA, single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

separately or collectively affect the number of branches plant^{-1} of tomato. Among various irrigation intervals, the highest number of branches plant^{-1} of 11.51 and 10.77 were recorded in 3- and 6-day irrigation intervals, respectively, while the lowest number of branches plant^{-1} of 8.15 was recorded in the 9-day irrigation interval. Apparently, a suitable irrigation interval is essential for tomato growth, whereas inadequate irrigation practices at any growth stage could negatively affect tomato growth. Moreover, a decreased irrigation interval (3 days) during a rainy season could result in water saturation, which might reduce tomato growth and increase the risk of disease in tomato. These results are in conformity with Samaila et al. (2011), who reported that very decreased or increased irrigation intervals negatively affected tomato growth. Therefore, a 6-day irrigation interval could be suggested as an adequate irrigation practice for tomato crop.

Among the treatments, black polythene and transparent polythene produced the maximum number of branches plant^{-1} of 15.33 and 14.11, respectively, while the lowest number of branches plant^{-1} of 6.89 was recorded in the weedy check. These results indicate that having less or no weed infestation results in the maximum number of branches plant^{-1} as compared to the weedy check. Moreover, among all the treatments, black polythene efficiently reduced weed infestation and prominently increased the number of branches plant^{-1}. Moreover, black polythene is a continuous weed management practice which is effective in controlling weeds throughout the crop growing season as compared to non-solarization treatments which have limited-time weed control efficacy. Moreover, previous findings have suggested that black polythene is effective in controlling weeds and enabling tomato to produce a greater number of branches plant^{-1} (Samih and Abubaker 2013).

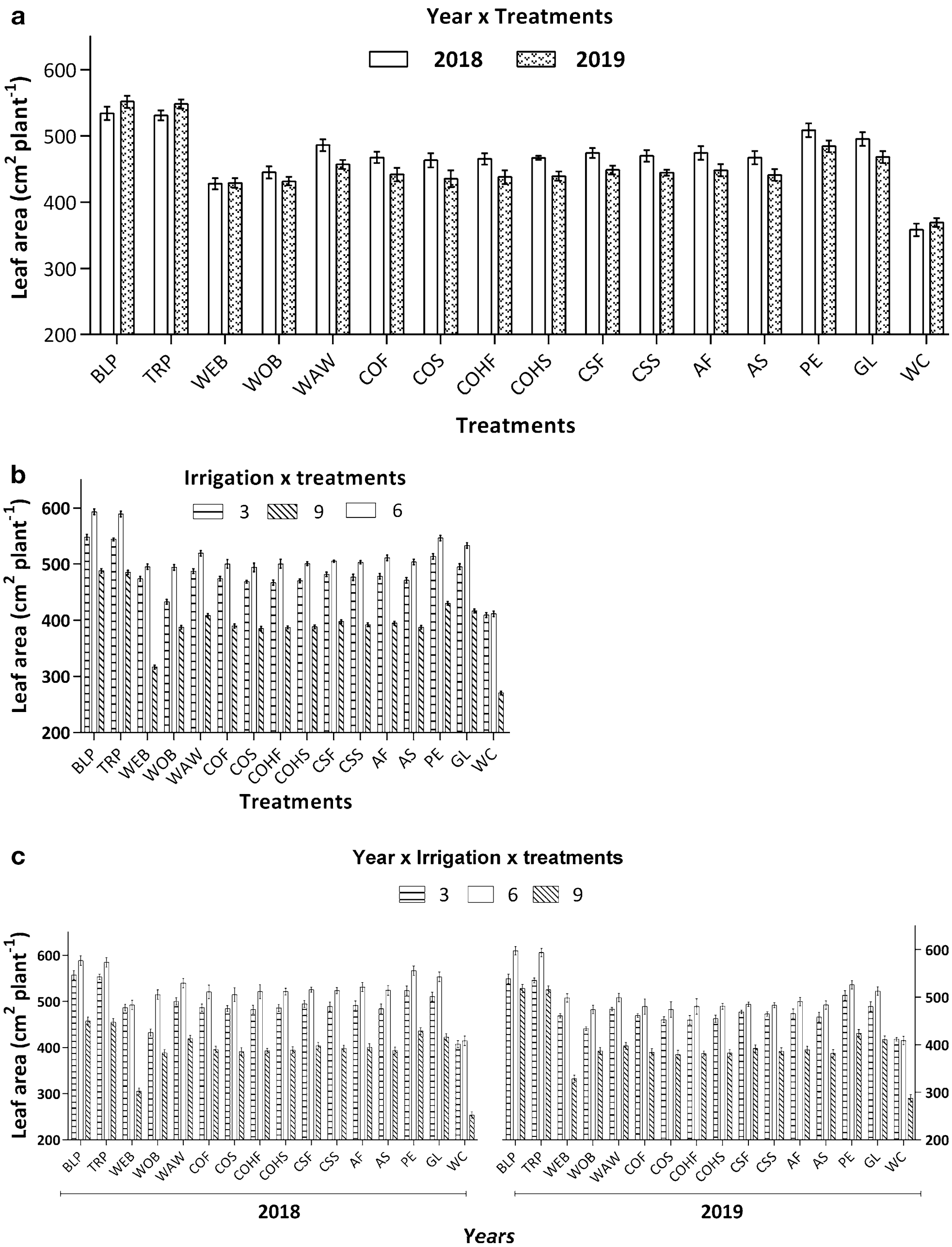


Fig. 11 Interaction of year × treatments (**a**), irrigation × treatments (**b**), and year × irrigation × treatments (**c**) on leaf area (cm^2) plant^{-1} of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

Leaf Area Plant^{-1} of Tomato

Combined-year statistical analysis of the data revealed that irrigation interval and treatments significantly ($P \leq 0.05$) affected the leaf area of tomato (Fig. 10). The results further showed that leaf area was significantly varied during both the growing seasons, where the highest leaf area (471.3 cm^2 plant^{-1}) was recorded in 2018 and the lowest leaf area (454.82 cm^2 plant^{-1}) was recorded in 2019. Similarly, the interaction among year × treatment (a), irrigation × treatments (b), and year × irrigation × treatments (c) was significant in both the years (Fig. 11). Moreover, the highest leaf area was produced by black polythene × 6-day interval during both the studied years. Additionally, the significant variation in the leaf area of tomato during both the years as well as the interactions could be due to variation in the weather pattern during 2018 and 2019 (Fig. 2).

Data regarding various irrigation intervals showed that the highest leaf area (512.64 cm^2 plant^{-1}) was recorded in the 6-day irrigation interval followed by the 3-day irrigation interval (489.76 cm^2 plant^{-1}), while the lowest leaf area (395.3 cm^2 plant^{-1}) was recorded in the 9-day irrigation interval. Water is a basic requirement for plant growth, whereas adequate irrigation practices improve tomato leaf area. Apparently, a 9-day irrigation interval causes some degree of water stress and increased *Orobanche cernua* weed

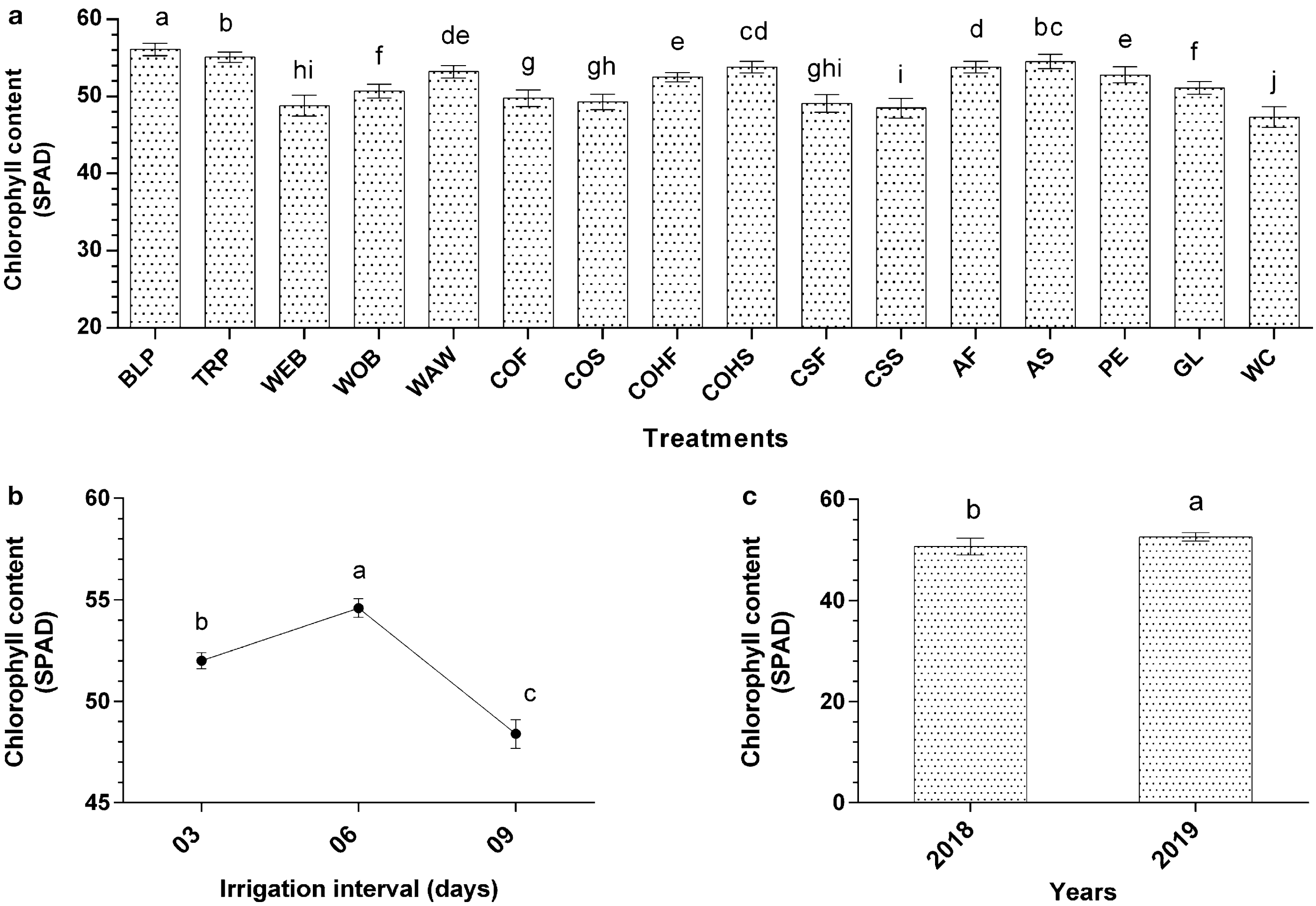


Fig. 12 Effect of irrigation intervals and weed control treatments on chlorophyll content (soil plant analysis development, *SPAD*) of tomato. **a** Effect of weed management treatments on chlorophyll content of tomato. **b** Effect of irrigation intervals on chlorophyll content of tomato. **c** Effect of years on chlorophyll content of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

density in tomato, which severely depletes the leaf area of tomato. Similarly, a 3-day irrigation interval also reduced the leaf area of tomato because of water saturation, which might render tomato prone to various diseases. Moreover, previous findings have revealed that tomato is sensitive to flooding conditions (Bray et al. 2000; Ezin et al. 2010). The results clarify that a 6-day irrigation interval is suitable for tomato growth under the current agroecological conditions.

Among the treatments, black polythene mulch resulted in the highest leaf area (543.05 cm^2 plant^{-1}) followed by transparent polythene (539.57 cm^2 plant^{-1}), values which are statistically similar to each other, followed by pendimethalin (496.72 cm^2 plant^{-1}), while the minimum leaf area (363.73 cm^2 plant^{-1}) was recorded in the weedy check (control) treatment. Apparently, the lowest fresh weed biomass in the black polythene, transparent polythene, and pendimethalin conditions could be the reason for the highest leaf area, whereas the lowest leaf area in the weedy check might be due to the maximum weed competition with crop. In fact, weeds compete with crop for water, nutrients, and sunlight, consequently reducing the leaf area and photosynthetic efficiency of plants. Moreover, crops with no weed competition are better able to harvest maximum sunlight, which could ultimately improve the leaf area, photosynthetic efficiency, and morphological growth of tomato crop. Among all of the weed management treatments, black polythene obtained the maximum leaf area (cm^2 plant^{-1}). Moreover, previous findings have confirmed that black polythene significantly increased the leaf area of tomato (Hanna 2000). Furthermore, black polythene is also effective in reducing disease incidence in tomato leaves, by keeping the foliage away from the soil that often contains disease-causing conidial spores (Jambhulkar et al. 2012; Bhujbal et al. 2015). Therefore, black polythene could be suggested as the best weed management practice in tomato crop.

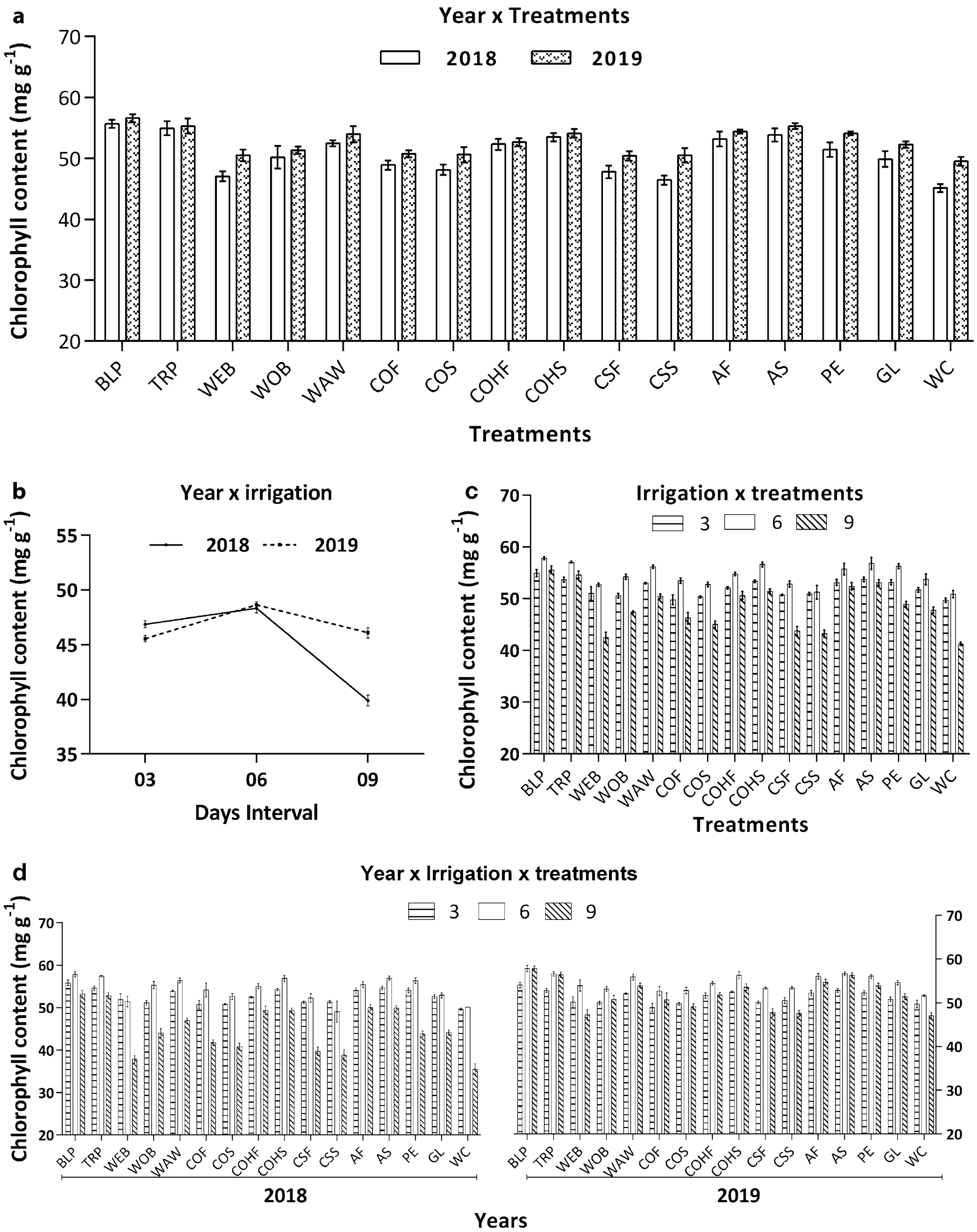


Fig. 13 Interaction of year × treatments (**a**), year × irrigation (**b**), irrigation × treatments (**c**), and year × irrigation × treatments (**d**) on chlorophyll content (soil plant analysis development, *SPAD*) of tomato. *BLP* black plastic, *TRP* transparent plastic, *WEB* weeding except broomrape, *WOB* sole weeding of broomrape, *WAW* weeding of all weeds, *COF* copper oxychloride (single dose) 2 kg ha^{-1}, *COS* copper oxychloride (split doses), *COHF* copper oxychloride + humic acid (HA; single dose), *COHS* copper oxychloride + HA (split doses), *CSF* copper sulphate (single dose) 2 kg ha^{-1}, *CSS* copper sulphate (split doses), *AF* ammonium sulphate (single dose), *AS* ammonium sulphate (split doses), *PE* pendimethalin 1.4 a.i ha^{-1}, *GL* glyphosate 48 SL 1.5 a.i ha^{-1}, *WC* weedy check (control)

Chlorophyll Content

Chlorophyll is the basic photosynthetic pigment and one of the major key indexes reflecting the photosynthetic efficiency of plants. Statistical analysis of data has revealed that various irrigation intervals and treatments significantly ($P \leq 0.05$) effect the leaf chlorophyll content of tomato. Moreover, combined ANOVA showed that both years have prominent variation in the chlorophyll content of tomato (Fig. 12). Similarly, the interactions among year × treatments (a), year × irrigation (b), irrigation × treatments (c), and year × irrigation × treatments (d) also significantly affect the chlorophyll content of tomato (Fig. 13). Apparently, variation in the chlorophyll content during the years and the significant interaction effect could be due to fluctuation in weather conditions and possibly variation in the daytime/nighttime temperature and rainfall frequency (Fig. 2).

Data regarding various irrigation intervals showed that a 6-day irrigation interval resulted in the highest chlorophyll content (54.55 SPAD) followed by a 3-day irrigation interval (51.99 SPAD), while the lowest chlorophyll content (48.39 SPAD) was recorded in the 9-day irrigation interval. The results confirmed that a decrease in irrigation interval from 9 to 6 days linearly increased the chlorophyll content of tomato; however, a further decrease in the irrigation interval to 3 days decreased the chlorophyll content in tomato. These results demonstrate that a severe increase or decrease in irrigation intervals negatively affects the chlorophyll content of tomato leaves. Moreover, a reduction in chlorophyll content could cause a substantial reduction in plant photosynthetic ability and, ultimately, reduce tomato growth (Mahlein et al. 2013). Consequently, a 6-day irrigation interval considerably increased chlorophyll content, which is adequate for tomato crop.

Among the treatments, black polythene resulted in the maximum chlorophyll content (56.10 SPAD), followed by ammonium sulphate at 200 kg ha^{-1} (split doses) with a chlorophyll content of 54.55 SPAD and transparent polythene with a chlorophyll content of 55.11SPAD, which are statistically similar. Moreover, the rest of the treatments produced an intermediate chlorophyll content ranging from 48.76 to 52.74 SPAD, values which are statistically comparable, while the minimum chlorophyll content (47.28 SPAD) was recorded in the weedy check. Chlorophyll content is an indicator of plant response to stress conditions (Mauromicale et al. 2008). Previous findings have evidenced that plant photosynthetic ability is adversely affected in dense weed populations and broomrape infestation considerably reduced chlorophyll pigment and photosynthetic activity compared to healthy plants (Disciglio et al. 2016; Zhang et al. 2017). Additionally, Faradonbeh et al. (2020) confirmed that the average chlorophyll content of infected plants was considerably lower in the weedy check as compared to the weed management treatments. Moreover, black polythene resulted in 16% higher chlorophyll content compared to the weedy check. A similar study by Sun et al. (2015) reported the highest chlorophyll content in black polythene mulch.

Conclusion

Chlorophyll content and other growth attributes of tomato were significantly affected by the irrigation intervals and weed management practices. Weeds, particularly *Orobanche,* directly drain water and nutrients from tomato plant and significantly reduce leaf chlorophyll content and the photosynthetic efficiency of tomato. Consequently, our 2-year field study revealed that integrating a 6-day irrigation interval with black polythene efficiently reduced *Orobanche* and other weeds, and considerably increased leaf chlorophyll content and other growth attributes of tomato crop. Hence, the present investigation could be suggested as a promising weed control strategy against *Orobanche* and other associated weeds of tomato crop.

Acknowledgements This article is based on the PhD thesis research of Mr. Muhammad Fawad. The financial support of the Agricultural Innovation Program-USAID/International Maize and Wheat Improvement Center and Pakistan Agriculture Agricultural Research Council for this study is highly appreciated. We gratefully acknowledge Dr. Adil Mihoub (Biophysical Environment Station, National Road N°3 Ain Sahara, Nezla-P.O. Box 360, Touggourt 30240, Algeria) and Mr. Aftab Jamal (Department of Soil and Environmental Sciences, Faculty of Crop Production Sciences, University of Agriculture, Peshawar 25130, Pakistan) for their technical help and constructive guidance throughout the writing of this manuscript.

Conflict of interest M. Fawad and M. A. Khan declare that they have no competing interests.

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