Weed management using tillage, seed rate and bed planting in 
durum wheat (Triticum durum Desf.) under an organic agriculture 
system

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ABSTRACT
Weed management is a major obstacle in conversion from conventional 
to organic agriculture system, and objective of this study was to manage 
weeds in organically grown durum wheat. The treatment combinations 
of conventional tillage (CT) or deep tillage (DT) with 50% higher plant 
densities, zero tillage (ZT) with and without residues, straw mulching 6 t ha−1 and bed planting plus 25% higher plant density followed by hand 
pulling were evaluated for weed control in durum wheat in a two-year 
study. Tillage has differential effect on weed seed distribution and more 
than 60% of weed seeds were concentrated in 0–7.5 cm soil layer in CT 
and ZT, whereas 50.9% of weed seeds were displaced to 15–30 cm soil 
layer in DT. Bed planting plus 25% higher plant density followed by hand 
pulling resulted in lowering of weed density and biomass by 61.2% and 
58.9%, respectively, at harvest. The maximum growth parameters, yield 
attributes and wheat grain yield, were obtained under bed planting with 
25% higher plant density and one hand pulling. Sowing of durum wheat 
on raised beds or ZT with residue retention may be used as an effective 
and economical weed management tool under organic agriculture 
systems.

Introduction
Durum wheat (Triticum durum Desf.) is an important food crop of the world, with an estimated 
36 million tons of annual global production. Durum wheat is used in preparation of macaroni, pasta 
products and semolina, and is one of dependable crop after rice and maize for the nourishment of 
world population including India. It is an economically important crop produced globally in 10–11% 
area of the world and accounts for around 8% of the global wheat production. The major producing 
countries are Turkey, Canada, Algeria, Italy and India. Durum wheat is similar in composition to 
common wheat, except that its kernels are very hard and have a different mineral distribution with 
kernel weight ranging from 35 to 60 mg. The quality of end-products is related to the quality of the 
durum grain, which, in turn, is mainly determined by the genotype and also influenced by the 
environment (weather and nutrition) and crop management.

Conventional crop production practices rely heavily on synthetic fertilizers to provide nutrition 
and pesticides to control weeds, insects and diseases for higher crop yields, which significantly
impact public health and the environment (Pimentel et al. 2005). Chemically intensive conventional agriculture has exerted great pressure on soils, water, atmosphere and biodiversity, and this pressure will be further exacerbated in the future keeping in mind the current trends in population growth. Sustainable and resilient agricultural practices while minimizing environmental and economic costs need to be followed to maintain the Earth’s capacity to produce agriculture systems (Mäder et al. 2002; Lynch et al. 2011). Organic farming is one of the several approaches for achieving sustainable agriculture goals. However, organic farming is based on specific regulations and certification programmes, which ban the use of all synthetic inputs (Kobierski et al. 2020). The concerns about nutritional security and environmental sustainability are making organic products more popular among consumers (Knowler and Bradshaw 2007; Scherr and McNeely 2008). The consumer demand for organic products has increased over years, which led to expansion of organic production. Global market demand for organic food has reached 81.6 billion USD.

Weeds are an important component of agricultural ecosystems, and weed communities play a significant role in the determination of the nature of weed management strategies to be adopted in crops and cropping system (Storkey and Cussans 2007; Travlos et al. 2018). There is more weed pressure in organic farming, and weed management is a major obstacle in conversion from conventional to organic agriculture system (Carr et al. 2013) and also, there is low crop yields under organic agriculture system than in conventional (Ponisio et al. 2015; Fernandez et al. 2019). To reduce the costs and risks involved in organic production systems, various cultural and mechanical weed management strategies need to be developed to improve productivity. Sole reliance on chemicals and mono-cropping has led to the problem of the evolution of herbicide resistance. The reduction of deleterious effects of the weeds on crops is the major goal of weed management. In any weed control practice, there is no substitute for good crop husbandry methods. The selective stimulation of crop growth can be achieved with the manipulation of soil and cropping condition in favour of crops. The crop environment can be manipulated by altering tillage or crop establishment method, seed rate (plant population) and mulching.

The use of primary and secondary tillage and mulches for weed management is allowed in organic farming systems. Tillage systems influence physical, chemical and biological properties of soil, and have a major impact on soil productivity and sustainability. There are very deleterious effects of long-term conventional tillage (CT), such as adverse effects on soil productivity due to soil erosion (due to wind or water) and loss of organic matter. Sustainable soil management can be achieved through zero tillage (ZT) with either retaining residue of the previous crop on the soil surface or ZT with residue removal (Hobbs et al. 2008). Weed density in initial crop period depends upon weed seed bank and tillage serves as weed management strategy to reduce the weed seed bank present in the different soil layers. CT or ZT or deep tillage (DT) affects vertical distribution of weed seeds within the soil profile (Cousens and Moss 1990) and helps in controlling weeds by burying weed seeds and emerged seedlings leaving a rough surface to hinder weed seed germination, expose underground parts of perennial weeds leading to their desiccation (Travlos et al. 2018).

In the ZT system, residues retained on the soil surface serve as a physical barrier for the emergence of weeds. Similarly, zero tillage may also lead to an early emergence of wheat and no or less soil disturbance in the cropped area resulting in less and late emergence of weeds especially Phalaris minor Retz. (Singh et al. 2010). The intensity of P. minor decreased by 30–40% by adopting ZT as compared to CT, while the intensity of broadleaf weeds increased (Singh et al. 2015). Grain yield is also increased in bed planting compared to flat planting mostly because of the deposition of more fertile topsoil on beds and weeds are concentrated mainly in furrows owing to the lack of crop cover there (Majeed et al. 2015). The bed planting system facilitates mechanical cultivation, an economical option as an alternative method of weed control during the crop growing season because of the easy field entry resulting from crop row orientation on the beds.

Seed and cropping density can affect weed population as the availability of growth resources to weeds decreased with an increase in crop density and thereafter crop yield losses decreased (Ramesh et al. 2017). Crop plants take more time to close their canopy with the use of low seeding
rates, which encourages weed growth. High seeding rates facilitate quick canopy closure, which helps to suppress weeds more effectively. The density of crops affected the competition of crops with weeds (Limon-Ortega et al. 1998; Evers and Bastiaans 2016). Mulching does not allow the light to reach to weeds by acting as a physical barrier, which affects weed emergence and growth. Crop residues can be effectively used for suppressing weeds in tilled (Singh et al. 2008) and untilled rice (Chauhan and Opeña 2012).

The efforts were made to develop effective weed management approaches for organically grown durum wheat production systems. The objectives of the present study were to evaluate the performance of differential tillage, planting densities, bed planting, straw mulching and hoeing as a weed management tool in durum wheat crop under organic agriculture system. It was hypothesized that differential tillage and planting density may affect weed seed distribution within soil profile and weed growth in the crop. The effect of non-chemical weed management methods of tillage, seed rate and bed planting on growth, yield and quality of durum wheat was studied.

Materials and methods

Site description, experimental design and treatment details

The field experiment was conducted for successive two years (2017–18 and 2018–19) at Research Farm, Department of Agronomy, Punjab Agricultural University, Ludhiana (30° 56’ N latitude, 75° 52’ E longitude and at an altitude of 247 m above mean sea level), India, during the winter season (November–April). It is situated in the Trans-Gangetic Agro-Climatic zone at and is characterized by a sub-tropical semi-arid type of climate. The mean maximum of 23.1°C-23.3°C and minimum temperature of 9.6°C were recorded during crop growth cycle in both years of study. The total rainfall of 79.4 mm and 206 mm was received during crop growth cycle of 2017–18 and 2018–19, respectively. The soil of the experimental field was typic Hapludalf (sandy loam containing 52.4% sand, 38.3% silt and 10.7% clay) with 7.1 soil pH (normal) and electrical conductivity of 0.19 dS m⁻¹. The soil was tested medium in organic carbon (0.42%), low in nitrogen (257.7 kg ha⁻¹) and medium in phosphorus (14.6 kg ha⁻¹) and potassium (163.1 kg ha⁻¹).

This experiment was conducted in randomized complete block design in three replicates with a total of 30 experimental units with gross plot size of 7.5 m × 5.0 m. Treatments were conventional tillage (CT) with (+) unweeded (T1), CT + weed-free (T2), CT + 50% higher plant density+ one hoeing (T3), CT + 50% higher plant density+ straw mulch 6 t ha⁻¹ (T4), deep tillage (DT) + 50% higher plant density + one hoeing (T5), DT + 50% higher plant density + straw mulch 6 t ha⁻¹ (T6), zero tillage (ZT) with residues + 50% higher plant density (T7), ZT without residues +50% higher plant density (T8) and CT + bed planting + 25% higher plant density + one hoeing (T9). One treatment of conventional agriculture + weed-free (T10) was kept for the comparison of growth, yield and quality of durum wheat crop with T2 treatment of organic agriculture treatments.

Field preparation and crop raising

Tillage for field preparation was done as per treatments except in ZT treatments (T7 and T8), where no-tillage operation was done. In ZT with residues (T7), residues (nearly 6 t ha⁻¹) of the previous rice crop were retained on the surface and wheat was directly sown with Happy Seeder (Mahal et al. 2019). The seed was drilled in 20 cm widely spaced rows, and rice straw was pressed as mulch in between the crop seeding rows. In ZT without residue (T8), rice residue was completely removed before sowing of wheat seed with Zero till drill. In CT treatments (T1-T4), two ploughings with plough depth of 0–15 cm done with disc plough were followed by planking operation. In DT treatments (T5 and T6), one ploughing with a mould board plough (inversion ploughing) with plough depth of 0–30 cm was done, which was followed by one cultivation operation by rotavator and planking operations. In T4 and T6 treatments, rice straw at 6 t ha⁻¹ was used as a mulching material for
covering soil surface immediately after sowing in the respective plots. In T9, furrow-irrigated raised bed sowing (FIRBS) using 25% more seed rate was done with the help of a wheat bed planter after field preparation with CT. In this, two rows of the wheat crop were sown at 20 cm row spacing on a 37.5-cm-wide bed with a 30-cm-wide furrow between two beds.

Durum wheat cv. WHD 943 (days to maturity: 145 days) was sown during the first week of November 2017 and 2018 as per treatments. To fulfill the nutrition demand of durum wheat crop as per the soil test report, 12.5 t ha\(^{-1}\) (on a dry weight basis) of well-decomposed farmyard manure was mixed in the soil before pre-sowing irrigation in T1–T9 treatments. For organically grown wheat crop (in T1-T9 treatments), consortium of Azotobacter and Streptomyces (Azo-S) biofertilizer of 250 g each was used to inoculate seed. The treated seed was used in variable seed rate for sowing in two different row spacing of 15 and 20 cm in the plots with different planting densities. For sowing with normal plant density (in T1, T2, T4 and T10), seed rate of 100 kg ha\(^{-1}\) and 20 cm row spacing was used. For sowing with 25% more plant density (in T9) and 50% higher plant density (in T3, T5, T6, T7 and T8), a total of 125 kg ha\(^{-1}\) and 150 kg ha\(^{-1}\), respectively, seed and 15 cm row spacing was used.

Weed-free plots (T2 and T10) in the experiment were kept free from weeds for the whole crop season by hand weeding and a total of seven weedings were done. Hand pulling of weeds was done once at 35 days of sowing (DAS) in plots of T3, T5 and T9 treatments. In the weedy plots (T1), weeds were allowed to grow for the whole crop season. In T10 treatment, CT operation was done for field preparation and synthetic inputs were used for crop production and protection practices. In T10 treatment, plot was kept weed-free for the whole crop season with the use of herbicides and hand pulling.

The first irrigation was applied at 20 days of sowing and follow-up irrigations were applied at intervals of 5–6 weeks to prevent the crop from water stress. During rainy days, no irrigation was applied and the last irrigation was given 15 days before crop harvest. The durum wheat crop in T1–T9 treatments was raised without using any chemical fertilizers or pesticides throughout its growing period.

**Data collection**

To measure weed seed reserve, soil samples were taken from four diagonal spots in respective plots with the help of core sampler of diameter 10.5 cm before and after tillage operations (CT and DT). The samples were taken separately from three soil depths: 0–7.5, 7.5–15 cm and 15–30 cm. Soil samples from three spots were mixed and washed with water using a 0.2-mm sieve cloth to separate weed seeds from the soil. In a laboratory, the seed samples were transferred to petri plates lined with wet filter papers. Germination tests were performed at 25–30°C temperatures and sufficient conditions of moisture were maintained in the plates. Weed seed germination was recorded at a weekly interval until no germination occurred in the dishes, and data were converted into viable weed seeds m\(^{-2}\).

The weed population and weed biomass were periodically recorded at 30 and 60 DAS and at harvest from each plot. Two representative quadrats each of 50 cm × 50 cm size were placed randomly in each plot, and the species-wise observations of weed density were recorded. For weed biomass, weeds were separated into the grass and broad-leaf weeds groups, and above ground weed biomass was sun-dried and placed in an oven at 65°C for 72 h for getting constant dry weight and was expressed in g m\(^{-2}\). Weed control efficiency (%) of a particular treatment was computed as:

\[
\text{Weed biomass in T1 treatment} - \text{Weed biomass in particular treatment} \over \text{Weed biomass in T1 treatment} \times 100
\]

Plant height was recorded from each plot from five randomly selected plants at harvest from ground level to the base of the spike. Tillers were counted from the third row from two spots of 50 cm row length in each plot at 60 DAS and expressed as the number of tillers m\(^{-2}\). Crop biomass
data were recorded at 60 DAS using the destructive method in which above-ground crop biomass was collected from 50 cm length of the second row from two places in each plot. The samples were kept for sun-drying before placing in the oven at 65°C for 72 h for constant dry weight and the dry biomass data was expressed in g m⁻². Effective tillers (spikes bearing tillers) were counted from the third row from two spots of 1-m row length in each plot at maturity and expressed as the number of effective tillers m⁻². The number of grains spike⁻¹ was counted manually from randomly selected five spikes at harvest. Harvested produce from the net plot was threshed manually and grain yield at 14% moisture content was recorded. The prevailing market prices were used for calculating economic returns under different treatments and benefit-cost ratio was calculated by dividing gross returns with total variable costs.

Test weight was determined using the apparatus developed by the Indian Institute of Wheat and Barley Research, Karnal, India, which employs a standard container of 100 mL capacity (Mishra 1998). The grains were weighed and the test weight was expressed in kg hl⁻¹. The grain hardness was measured by using the grain hardness tester supplied by M/s Ogawa Seiki Co. Ltd., Japan by crushing 10 grains one by one selected randomly from the lot. The mean force (kg) required to crush the grain was recorded. The grain protein content was estimated using the whole grain analyzer infratec 1241 supplied by M/s Foss Analytical AB, Sweden, the instrument uses the near-infrared light transmitted through the grains. The grain samples are scanned in the range of 850–1050 nm with a bandwidth of 7 nm, and there are 100 data points per scan. The results are displayed as percentage protein content. In total carotenoids, 4-g wheat flour and 20-mL water-saturated butanol were added to each tube and samples were kept for 16 h in dark. After incubation, all the samples were filtered through Whatman filter paper No.1 and the sample was allowed to stand for 20 min at room temperature. The absorbance was read at 440 nm. Incidence of the yellow berry was recorded by observing yellow spots on the kernels on a percentage basis (Blandino et al. 2015). The wheat grain sample (50 g) was placed on a very clean white filter paper and observed grains with yellow spots, and the results were expressed on percentage basis.

**Data analysis**

The data were pooled from 2017–18 to 2018–19 years based on covariance parameter estimates and homogeneity of variance tests. Heterogeneity of variance was modelled using the repeat option. The data on weed count and dry weight accumulation were subjected to square-root transformation (\(\sqrt{x+1}\)) before statistical analysis. The data set of T1-T9 treatments was analyzed using PROC GLM procedures in SAS version 9.4 (SAS Institute, 2018). The differences between means of treatment effect of T2 and T10 for crop growth, yield attributes and quality were also analyzed using CONTRAST procedures in SAS. Treatment effects were declared significant at \(\alpha = 0.05\). Differences between means were compared using the least square means (LSMEANS) procedure and Tukey HSD (honest significant difference) post-hoc tests.

**Results**

**Weed seed bank studies**

Tillage system exerted a significant effect on weed seed bank of mainly five weed species. Four broadleaf weeds, namely, *Anagallis arvensis* L. (scarlet pimpernel), *Medicago denticulata* L. (burclover), *Rumex dentatus* L. (toothed dock), *Chenopodium album* L. (lambquarters) and only one grass weed, *P. minor* (littleseed canarygrass) were observed in the weed seed bank study at 0–7.5 cm, 7.5–15 cm and 15–30 cm soil depths (see Supplementary Figure S1). *Anagallis arvensis* was the dominant weed in the weed seed bank studies, followed by *M. denticulata*. Before tillage, there was almost a similar trend of distribution of the weed seeds in different soil layers from 0 cm (surface) to 30 cm soil depth (Figure 1). The top layer of 0–7.5 cm contained about 61–67% of total
Seed of different weed species. In CT treatment, around 94–96% of the weed seeds were concentrated in 0–15 cm soil layer. The deeper layer of 15–30 cm consisted of the minimum weed seeds, and only 4–6% of weed seeds was observed after CT operations out of total weed seed bank. There was similar vertical weed seed distribution in different soil layers in CT and ZT treatments. In DT, the lower number (14–23% only) of weed seeds was observed in the top layer of 0–7.5 cm soil depth (Figure 1). The deep and inversion tillage in DT treatment resulted in displacement of 43–53% of weed seeds to deeper layer of 15–30 cm for all weed species under study (Figure 1 and S1).

**Weed density**

Weed flora of the experimental field consisted mainly of broadleaves namely *A. arvensis*, *Coronopus didymus* L. (lesser swine cress), *R. dentatus*, *Medicago denticulata*, *Melilotus indica* L. (sweet clover), *Spergula arvensis* L. (sandweed) and *C. album*. Among grasses, *P. minor* was observed. The field was influenced by broadleaves, and *A. arvensis* was one of the dominant weeds followed by *Coronopus didymus* and *Chenopodium album*. Weed management techniques significantly influenced the population of weed species at 30 DAS as differential tillage and plant density resulted in lower weed density than the unweeded (T1). The density of *P. minor* (2 m$^{-2}$) was the lowest in ZT with residues + 50% higher plant density (T7) at 30 DAS (Figure 2). The maximum density of broadleaves (83.7 m$^{-2}$) was observed in T1 treatment, and the effect was species-specific. The density of *A. arvensis* was lower in CT with straw mulch (T4) or DT (T5 and T6) or ZT with residues (T7) or bed planting (T9) at 30 DAS. The density of *M. denticulata* was lower in CT (T3 and T4) or DT (T5 and T6) or ZT (T7 and T8) or bed-planted wheat (T9) along with higher plant density as compared to T1. However, density of *M. indica* was similar in all treatments (T1 to T9) at 30 DAS. Straw mulching after CT (T4) or DT (T6) with 50% higher plant density and ZT along with residue retention (T7) have added advantage in restricting weed growth and resulted in lower weed density as compared to CT (T3) or DT (T5) without mulching and ZT without residues (T8). DT with 50% higher plant density along with straw mulching (T6) resulted in the minimum density of *C. album* which was similar to that of weed-free. CT+ bed planting + 25% higher plant density (T9) resulted in a lowest number of broadleaf weeds except that of *S. arvensis* and *R. dentatus* at 30 DAS, and it was statistically comparable to CT+50% higher plant density with straw mulching (T4), DT+50% higher plant density (T5 and T6) and ZT with residues (T7).
Figure 2. Effect of tillage, seed rate and bed planting on weed density of (A) Anagallis arvensis (B) Coronopus didymus (C) Rumex dentatus (D) Medicago denticulata (E) Chenopodium album (F) Spergula arvensis (G) Melilotus indica and (H) Phalaris minor at 30 DAS, 60 DAS and harvest in organically grown durum wheat crop. Treatments are T1: conventional tillage + unweeded; T3: conventional tillage + 50% higher plant density + one hoeing; T4: conventional tillage + 50% higher plant density + straw mulch 6 t ha⁻¹; T5: deep tillage + 50% higher plant density + one hoeing; T6: deep tillage + 50% higher plant density + straw mulch 6 t ha⁻¹.

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Figure 2. Hand pulling of weeds at 35 DAS resulted in lower weed density in these plots. At 60 DAS, maximum weed density was found in the unweeded plot (T1), which was statistically similar to weed population observed in ZT without residues and CT + 50% higher plant density with straw mulch 6 t ha⁻¹ (T8). At harvest, lowest weed density was observed in CT + bed planting + 25% higher plant density followed by hoeing, which was statistically similar to DT+50% higher plant density along with straw mulching (T6) and ZT with residue retention with 50% higher plant density (T7).

Weed biomass

Weed biomass of grasses and broadleaves at 30 and 60 DAS and at harvest exhibited significant differences amongst treatments (Figure 3). ZT with residues + 50% higher plant density (T7) resulted in 100% control of grasses at 30 DAS. The maximum grass weed biomass of 9 g, 31.5 g and 79 g m⁻² was observed in unweeded treatment (T1), and it was significantly more than rest of treatments at 30, 60 DAS and at harvest, respectively. The biomass of grass at 60 DAS was significantly lower in plots receiving hand pulling of weeds after CT (T3) or DT (T5) or bed-planted wheat (T9) with higher plant density. Grass weed biomass was observed statistically similar in plots of CT (T3 and T4) or DT treatments (T5 and T6) or ZT with or without residues (T7 and T8) or bed-planted wheat (T9) at 30 DAS and at harvest. Bed-planted wheat (T9) resulted in 67.1% control of grasses at harvest. The biomass of broadleaves was the maximum in unweeded (T1) at all intervals (Figure 3). Weed biomass of broadleaves was the lowest in CT + bed planting + 25% higher plant density + one hoeing (T9) at
30 and 60 DAS, and it was similar to weed biomass in the rest of weed control treatments comprising of differential tillage (CT or ZT or DT), plant density (normal, 25% or 50%) more plant density and straw mulching or hand pulling except unweeded (T1). At harvest, higher biomass of broadleaves was observed from CT + unweeded (T1) and lower biomass was found in CT + bed planting + 25% higher plant density + one hoeing (T9). ZT without residue retention (T8) had similar biomass of broadleaves to unweeded (T1); however, it (T8) resulted in lower grass weed biomass than unweeded at harvest. At harvest, bed planted wheat (T9) resulted in 57.3% control of grasses, and it was seconded by ZT with residues + 50% higher plant density (T7) and DT + 50% higher plant density + straw mulch 6 t ha⁻¹ (T6) with 45.6% control.

At harvest, CT + bed planting + 25% higher plant density + one hoeing resulted in 58.9% weed control efficiency (Table 1). Treatments with straw mulching in plots of CT (T4) and DT (T6) and ZT with residue retention (T7) resulted in 33.4%, 48.2% and 47.8%, respectively, weed control at harvest. The lowest weed control efficiency was observed in in CT+50% higher plant density + hoeing (T3) and ZT with residues (T7).

Crop growth

Weed management techniques involving differential tillage (CT or DT or ZT with and without residues) with higher planting densities and bed planting resulted in a statistically similar plant height (Table 1). Among the treatments, the maximum number of tillers (348 m⁻²) at 60 DAS was found in CT+ bed planting + 25% higher plant density + hoeing (T9), which was statistically similar to other weed management techniques involving differential tillage with higher plant density and straw mulching. The number of tillers was numerically lower in unweeded (239 m⁻²). The minimum crop biomass was reported in unweeded (T1), which was statistically similar to the rest of cultural weed management practices such as differential tillage, plant density and hand hoeing except bed planting (T9) and weed-free (T2) treatments. Organically grown durum wheat crop under weed-free conditions (T2) resulted in statistically similar plant height, number of tillers and crop biomass at 60 DAS to conventional durum wheat crop (T10).

A higher number of effective tillers (344 m⁻²) were observed in CT + weed-free (T2), and it was seconded by CT + bed planting + 25% higher plant density + one hoeing (T9) treatment, which was significantly more than the rest of cultural weed management practices. The maximum number of grains spike⁻¹ (38.7 grains) was observed in CT+ bed planting + 25% higher plant density + one hoeing (T9), while a lower number of grains was observed in unweeded (T1) treatment. Although, differences were non-significant amongst all treatments of differential tillage, plant density and hand hoeing. Organically grown durum wheat crop under weed-free conditions (T2) resulted in statistically similar number of effective tillers and grains spike⁻¹ to conventional durum wheat crop (T10).

Grain yield, quality and economics

The effect of weed management methods on the wheat grain yield was significant (Table 1). In the case of organic weed control treatments (T1 to T9), lowest grain yield and economic returns were obtained from the unweeded (T1). The maximum grain yield, harvest index and B:C ratio of 4.6 t ha⁻¹, 65.6 and 2.36, respectively, was obtained in CT-weed free (T2) treatment.

It was seconded by CT + bed planting + 25% higher plant density + hoeing (T9), which resulted in similar grain yield to CT + 50% higher plant density + hoeing (T3) and ZT with residues + 50% higher plant density (T7) treatments. The follow-up treatment of hoeing at 35 DAS in treatments of CT (T3) and DT (T5) with 50% higher plant density resulted in more grain yield as compared to straw mulching at sowing (T4 and T6) in these treatments.

The grain yield and other yield attributes were numerically more under the conventional agriculture system (T10) but it was statistically similar to T2 treatment. All quality parameters of durum wheat such as moisture content, protein content, test weight, grain hardness, total
**Table 1.** Crop growth parameters at 60 DAS, weed control efficiency, yield attributes, yield of durum wheat crop and economics of different treatments (average of two years).

| Treatments | Crop growth attributes | Weed control efficiency at harvest (%) | Yield and yield attributes | Benefit:Cost ratio |
|------------|------------------------|----------------------------------------|---------------------------|-------------------|
|            | Plant height* (cm)     | Tillers at 60 DAS* (No. m⁻²)           | Crop biomass at 60 DAS* (g m⁻²) | Effective tillers* (No. m⁻²) | Grains spike⁻¹* (No.) | Grain yield* (t ha⁻¹) | Harvest index (%) |
| T1         | 76.8 a                 | 239 b                                  | 207 b                     | -                             | 207 b                   | 39.9 a                   | 2.150 c             | 38.5               | 1.10       |
| T2         | 77.2 a                 | 326 a                                  | 344 a                     | 100.0                         | 344 a                   | 38.2 a                   | 4.600 a              | 65.6               | 2.36       |
| T3         | 76.9 a                 | 285 ab                                 | 275 ab                    | 14.6                          | 275 ab                  | 38.5 a                   | 3.518 ab             | 51.9               | 1.77       |
| T4         | 77.2 a                 | 287 ab                                 | 270 ab                    | 33.4                          | 270 ab                  | 38.5 a                   | 3.277 abc            | 50.9               | 1.65       |
| T5         | 77.2 a                 | 289 ab                                 | 275 ab                    | 35.5                          | 275 ab                  | 38.2 a                   | 3.419 abc            | 50.1               | 1.67       |
| T6         | 77.1 a                 | 286 ab                                 | 274 ab                    | 48.2                          | 274 ab                  | 38.4 a                   | 3.237 bc             | 47.8               | 1.59       |
| T7         | 77.3 a                 | 291 ab                                 | 282 ab                    | 47.8                          | 282 ab                  | 38.2 a                   | 3.507 ab             | 51.3               | 1.82       |
| T8         | 77.4 a                 | 295 ab                                 | 284 ab                    | 19.1                          | 284 ab                  | 38.4 a                   | 3.478 abc            | 51.0               | 1.80       |
| T9         | 77.7 a                 | 348 a                                  | 323 a                     | 58.9                          | 323 a                   | 38.7 a                   | 4.536 ab             | 63.8               | 2.30       |
| T10        | 77.7 ns                | 359.9 ns                               | 349.5 ns                  | 100.0                         | 349.5 ns                | 40.6 ns                  | 5.131 ns             | 68.1               | 2.63       |

*Treatments are T1: Conventional tillage (CT) with (+) unweeded, T2: CT + weed-free, T3: CT + 50% higher plant density+ one hoeing, T4: CT + 50% higher plant density+ straw mulch 6 t ha⁻¹, T5: deep tillage (DT) + 50% higher plant density + one hoeing, T6: DT + 50% higher plant density + straw mulch 6 t ha⁻¹, T7: Zero tillage (ZT) with residues + 50% higher plant density, T8: ZT without residues +50% higher plant density and T9: CT + bed planting + 25% higher plant density + one hoeing, T10 treatment of conventional agriculture +weed-free was kept for comparison with T2 treatment of organic agriculture system.*

*Mean values in each column not connected by the same letter are significantly different according to Tukey’s HSD (α = 0.05).*
Table 2. Quality parameters of grains of durum wheat under different treatments (average of two years).

| Treatments# | Moisture content (%)* | Protein content (%)* | Test weight (g L⁻¹)* | Yellow berry (%)* | Grain hardness (kg grain⁻¹)* | Total carotenoids (mg kg⁻¹)* |
|-------------|-----------------------|----------------------|----------------------|--------------------|-----------------------------|------------------------------|
| T1          | 9.70 a                | 10.4 a               | 78.4 a               | 16.1 a             | 11.9 a                      | 5.40 a                       |
| T2          | 9.45 a                | 10.7 a               | 79.1 a               | 16.2 a             | 11.7 a                      | 5.30 a                       |
| T3          | 9.75 a                | 10.2 a               | 79.0 a               | 16.6 a             | 12.1 a                      | 5.40 a                       |
| T4          | 9.80 a                | 10.6 a               | 79.2 a               | 16.1 a             | 11.7 a                      | 5.40 a                       |
| T5          | 9.55 a                | 10.4 a               | 79.5 a               | 16.7 a             | 12.2 a                      | 5.40 a                       |
| T6          | 9.75 a                | 10.4 a               | 79.0 a               | 16.7 a             | 11.7 a                      | 5.40 a                       |
| T7          | 9.70 a                | 10.2 a               | 79.4 a               | 16.5 a             | 11.7 a                      | 5.30 a                       |
| T8          | 9.65 a                | 10.7 a               | 79.2 a               | 16.5 a             | 12.6 a                      | 5.45 a                       |
| T9          | 9.70 a                | 10.2 a               | 79.5 a               | 15.7 a             | 12.2 a                      | 5.50 a                       |
| T10         | 10.1 ns               | 10.3 ns              | 80.0 ns              | 16.3 ns            | 12.1 ns                     | 5.55 ns                      |

* Treatments are T1: Conventional tillage (CT) with (+) unweeded, T2: CT + weed-free, T3: CT + 50% higher plant density + one hoeing, T4: CT + 50% higher plant density + straw mulch 6 t ha⁻¹, T5: deep tillage (DT) + 50% higher plant density + one hoeing, T6: DT + 50% higher plant density + straw mulch 6 t ha⁻¹, T7: Zero tillage (ZT) with residues + 50% higher plant density, T8: ZT without residues + 50% higher plant density and T9: CT + bed planting + 25% higher plant density + one hoeing. T10 treatment of conventional agriculture + weed-free was kept for comparison with T2 treatment of organic agriculture system. * Mean values in each column not connected by the same letter are significantly different according to Tukey's HSD (α = 0.05).

carotenoids and yellow berry incidence were statistically at par in cultural weed management practices such as differential tillage, plant density, mulching and hand hoeing to unweeded treatment (Table 2). The quality of durum wheat was similar in conventional and organic agriculture systems.

Discussion

The weed seed bank and density were different under differential tillage treatments. The 94–95% of weed seed bank was concentrated in the upper 0–15 cm soil layer under CT and ZT with or without residue, and only 5–6% of weed seeds were observed in lower soil layer of 15–30 cm. However, the top soil layer was inverted to lower soil layers in DT, which resulted in displacement of 44–54% of weed seeds in 15–30 cm soil layer (Figure 1 and S1). The largest proportion (90%) of the seed bank from the top 5 cm of the soil emerged under a ZT system compared to only 1% at a depth of 10–15 cm (Sinha and Singh 2005). Further, microbial decay of weed seeds under ZT systems is not so fast (Gallandt et al. 2004), and proportions of decayed seeds are similar under ZT and CT systems. Deep tillage was also found significant in reducing weed seeds in the upper soil layer, which is in line with the results of Mishra et al. (2005) who observed that deep tillage significantly reduced the population of weeds compared to the ZT system due to the deeper placement of most of the weed seeds which could not emerge out.

The minimum weed density was observed in the weed-free plots (T2). ZT with residues (T7), CT or DT with straw mulch (T4 and T6) and CT + bed planted (T9) along with higher plant density have a lower population of weeds at 30 DAS, which implied that residue retention or mulching at sowing time or sowing of the crop on beds have an edge from the weed control point of view and keep the growth of weeds under control. This indicated that straw mulch was found effective in reducing weed emergence and was able to prevent crop-weed competition during the initial 30 days. The findings by Ranjit and Suwanketnikom (2003) supported these results that straw mulch suppressed grass weeds by 23% and broadleaf weeds by 36% compared to weedy at 4 weeks of sowing of wheat. The minimum weed density was observed in the weed-free plot. ZT with residues (T7), CT or DT with straw mulch (T4 and T6) and CT + bed planted (T9) along with higher plant density have a lower population of weeds at 30 DAS, which implied that residue retention or mulching at sowing time or sowing of the crop on beds have an edge from the weed control point of view and keep the growth of weeds under check.
Tillage methods modify nutrient status and soil ecology in terms of temperature and moisture besides having its effect on weed seeds (Plaza et al. 2011), which ultimately affects the composition, abundance and density of weed species. In our study, the effect of tillage was differential on density and biomass of different weed species. Although, there was reduction in seeds of broadleaf weeds in upper soil layer of 0–7.5 cm due to DT as compared to CT or ZT (Figure 1 and S1). Still, density of broadleaf weeds at 30 DAS was not affected due to CT (T3 and T4) or DT (T5 and T6) or ZT (T7 and T8), which indicated that enough weed seeds were present in the weed seed bank of the upper soil layer (0–7.5 cm) irrespective of tillage treatments that resulted in similar weed density and biomass in all treatments (Figures 2 and 3). It implies that there was no effect of deep ploughing on weed density and biomass production, suggesting that although inversion ploughing resulted in displacement of more than 50% weed seeds to deeper layer (Figure 1), still whole soil profile of 0–30 cm have sufficient weed seeds that resulted in similar weed growth in all tillage treatments (Figures 2 and 3). Moreover, bold-seeded broadleaf weeds can emerge from deeper layers of soil. The small-seeded grass weed (P. minor) biomass was significantly less in different tillage and straw mulching treatments than the unweeded treatment. The density and biomass of P. minor were reduced under ZT with residues (T7) at 30 DAS. This is in agreement with findings of Anderson (2005) which observed that grass weeds were effectively managed under zero tillage systems as compared to conventional tillage, which was attributed to surface residue cover in zero tillage and reduced viability of seeds placed on the surface. Moreover, weed seeds lying on the soil surface are removed due to predation by granivorous fauna (Nichols et al. 2015).

As the crop age advances, the differential tillage, planting density and straw mulching fail to keep weed under control as more weed density and biomass were observed at 60 DAS. The hand weeding at 35 DAS helped in controlling weeds at the later stage of crop growth. The weed density was reduced after hoeing in DT or CT +50% higher plant density (T3 & T5) and CT + bed planting + 25% higher plant density (T9). As weed biomass in the crop is an indication of the competition given by weeds and more weed biomass indicate the intense crop-weed competition. Vigorous crop growth in bed planting (T9) put the crop at competitive advantage than weeds at later stages of crop growth (at 60 DAS and at harvest) and resulted in effective weed control; while weeds were fairly controlled by other treatments of tillage systems, variable plant density, straw mulching, residue retention and hand pulling (Figure 3 and Table 1).

Broadleaf weeds were dominant in the experimental field while density of grass weeds was low. As the crop age advanced, wheat crop covered short-statured dominant weed species such as A. arvensis, C. didymus and S. arvensis after 60 days (Figure 2). Broadleaves were at competitive disadvantage in terms of crop-weed competition because of their height which resulted in very low weed biomass of broadleaf weeds in spite of the abundance of these weeds in the experimental field. Further, Medicago denticulata and Melilotus indica belong to Fabaceae family and symbiotic nitrogen fixation took place due to the presence of nodules on the roots of these two weeds in this experiment (data not shown). It was observed in this study that more density of these broadleaf weeds in different treatments did not result in more reduction in grain yield of durum wheat crop and grain yield was statistically similar (Table 1). This implies that study of composition of weed species in a field is more important than total weed density and biomass. This implication is supported by work of Derksen et al. (1995) which observed that the diversity of weed species within communities and their interplay are of agronomic importance from economic perspective and decide the extent of crop-weed competition for applied plant nutrients and crop yield reduction. The density of P. minor is very low under ZT conditions while that of R. dentatus is more under the ZT system (T7 and T8) in the initial 60 days of crop growth (Figure 2). Broadleaves, namely, R. dentatus and C. album were tall-statured weeds and are the prominent weeds of wheat crop in the rice-wheat cropping system in North-West India. Phalaris minor mostly germinates from upper soil profile of 0–2.5 cm soil depth only while broadleaves due to their bold seed size can germinate from the deeper soil layers.
The selective stimulation of crop growth can be achieved with manipulation of soil and cropping condition with altering tillage or crop establishment method, seed rate (plant population) and mulching. The plant height and crop biomass of durum wheat were increased due to bed planting (border effects), which ultimately affected the grain yield. Bed planting (T9) was effective in reducing weeds. These results are in agreement with the results of Majeed et al. (2015) who reported that bed planting of wheat not only improved water and fertilizer use efficiency but also produced 15.1% higher grain yield than flat planting. Although different tillage treatments of CT or DT or ZT with residues along with higher planting densities and straw mulch resulted in differential effect on weed density and biomass. However, grain yields were comparable in differential treatments and plant density levels. It has been seen that weed diversity is more in the organic agriculture system and the extent of crop-weed competition is mainly affected by fertility management. It was observed in earlier studies that reduced tillage treatments in spite of more weed pressure resulted in similar grain yield to conventional tillage treatments in organic agriculture systems (Armengot et al. 2015). However, Fernandez et al. (2019) reported that wheat yields were higher under high tillage intensity (CT or DT) than low tillage intensity, and viability of no-tillage (ZT or minimum tillage), and viability of zero tillage was not for more than a few years.

The yield levels obtained under different treatments of organic agriculture systems (T2) were lower than conventional agriculture plots (T10), although the differences were non-significant (Table 1). The environmental conditions in organic and conventional systems are different which have a profound effect on crop yield through its effect on weed dynamics and nutrient supply (Campiglia et al. 2015). However, Ryan et al. (2009) suggested that organic agriculture systems may be able to tolerate more weed pressure as compared to conventional systems. The yields under different treatments of organic agriculture systems (T3 to T9) were statistically similar to each other, but it was numerically lower (0.595–1.894 t ha\(^{-1}\) lower) than conventional agriculture treatment (T10). The earlier studies also suggested that the yields in the organic agriculture system were 19.2 \pm 3.7\% lower than the yield level in the conventional agriculture system (Ponisio et al. 2015). Benaragama et al. (2016) reported 44\% lower grain yield in the organic agriculture system than the conventional agriculture system even under weed-free conditions. This indicated that weeds may not be responsible for yield reduction under the organic agriculture system and other factors such as lower soil productivity of the organic agriculture system play a major role in the decline in yields.

The protein content of durum wheat is a key factor in determining the suitability of wheat for different products. It was observed in our study that different grain quality parameters such as protein content, test weight, grain hardness and total carotenoids of durum wheat was not enhanced due to organic cultivation for two years as compared to conventional agriculture practices (Table 2). This can be due to the fact that grain quality is dependent on the genetic makeup of wheat varieties and is largely influenced by agronomic and climatic conditions (Blandino et al. 2015). Ponisio et al. (2015) opined that the organic agriculture system in the long-term studies performed better on some sustainability metrics, including improved crop quality, soil fertility, species richness and abundance, water holding capacity and energy use efficiency than conventional agriculture. It takes 3 years to convert a conventional agriculture field to an organic farm. The experimental field used in the study was in this phase of transformation and the benefits reported in organic agriculture farms were not truly seen there. This implies that this study needs to be conducted on long-term basis so that the real impact of differential tillage, planting density and straw mulching under organic agriculture system can be quantified.

Conclusions

In spite of the non-decisive results of tillage, plant density and sowing methods on crop yield, it is concluded that sowing of durum wheat crop on raised beds or in residue retained fields with ZT using 25–50\% more plant density will result in efficient and economical weed control and higher productivity of durum wheat under organic agriculture system.
Disclosure statement

No potential conflict of interest was reported by the author(s).

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