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Research article

Utilization of byproducts of sheep farming as organic fertilizer for improving soil health and productivity of barley forage

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ABSTRACT

Wool is a biodegradable fiber, rich in nutrients and can be recycled in soil as a fertilizer for maximum benefits. The present study was planned with the hypothesis that waste wool could be used as a nutrient source or manure to forage crops and aim of this study was to identify practicable recycling options of sheep based wastes in agriculture. In our study, we have compared the effect of different sheep based organic wastes on soil health, crop productivity and water use. Application of waste wool in soil significantly improved the fertility status of soil, and considerable improvement was also observed in organic carbon and nitrogen, i.e. around 30.8 and 32.6% higher over control. The activities of soil enzymes were 10–30% and 3–20% higher in waste wool treatment as compared to control and sheep based manures, respectively. Application of waste wool not only improved soil health but produced 50% higher grain and dry fodder yield of barley over control. The improvement in physical properties of soil with waste wool resulted in higher water use efficiency of the system. Our study will help in distinguishing choices for safe use of organic wastes along with up gradation of soil health and crop water utilization, particularly in nutrient poor soils of arid and semi-arid region of India.

1. Introduction

Generation of animal based bio-wastes has increased due to upsurge in food production leading to huge loads of organic waste in environment (Manna et al., 2018). Globally, India ranks seventh in wool production (1.8%), especially coarse wool with a productivity of 0.600 kg/sheep/year. In wool processing industries, nearly 10–15% wool is considered as waste obtained during processing and discarded or dumped as such on ground (Sharma et al., 2019). Waste wool is light, voluminous and proteinaceous in nature. Though wool is biodegradable, air floating fine particles of waste wool is harmful for human health and may cause serious environment hazards. Further, improper use of animal by-products results in outbreak of serious diseases such as foot and mouth disease, classical swine fever, avian flu and bovine spongiform encephalopathy. Therefore, the need of the hour is to have efficient environment friendly wool waste disposal system to overcome this problem (Zoccola et al., 2015). In today's agriculture, recycling of wastes is of major importance due to increasing demand of conserving natural resources and energy (Abdel-Shafy and Mansour, 2018).

Organic amendments in soil are progressively promoted irrespective of origin as an alternate to synthetic fertilizers for better soil health and sustainability (Luo et al., 2018). Scientific recycling of organic waste will help in reducing environmental pollution, along with improved crop productivity and soil health (Abdallah et al., 2019). Unclean sheep wool comprises of 50% carbon, 14.6% nitrogen, 5% sulphur and trace elements (cobalt, copper, iron, manganese, zinc and molybdenum) which play a vital role in plant nutrition (McNeil et al., 2007; Ordiales et al., 2016) and partial break down of waste wool by alkaline hydrolysis can make it a slow release fertilizer. Furthermore, waste wool also act as water conservation substrate in agriculture sector as it retains substantial amount of moisture (Mubarak et al., 2009; Kadam et al., 2013; Zoccola et al., 2015) when used as manure. Application of waste wool in tomato and pepper raised their yield by 30% (Zheljazkov, 2005) and also improved soil salinity and nitrogen content (Górecki and Górecki, 2010). Hence, waste wool when added to the soil, increases yield of crops (Adi and Pacurar, 2015), absorbs and retains soil moisture

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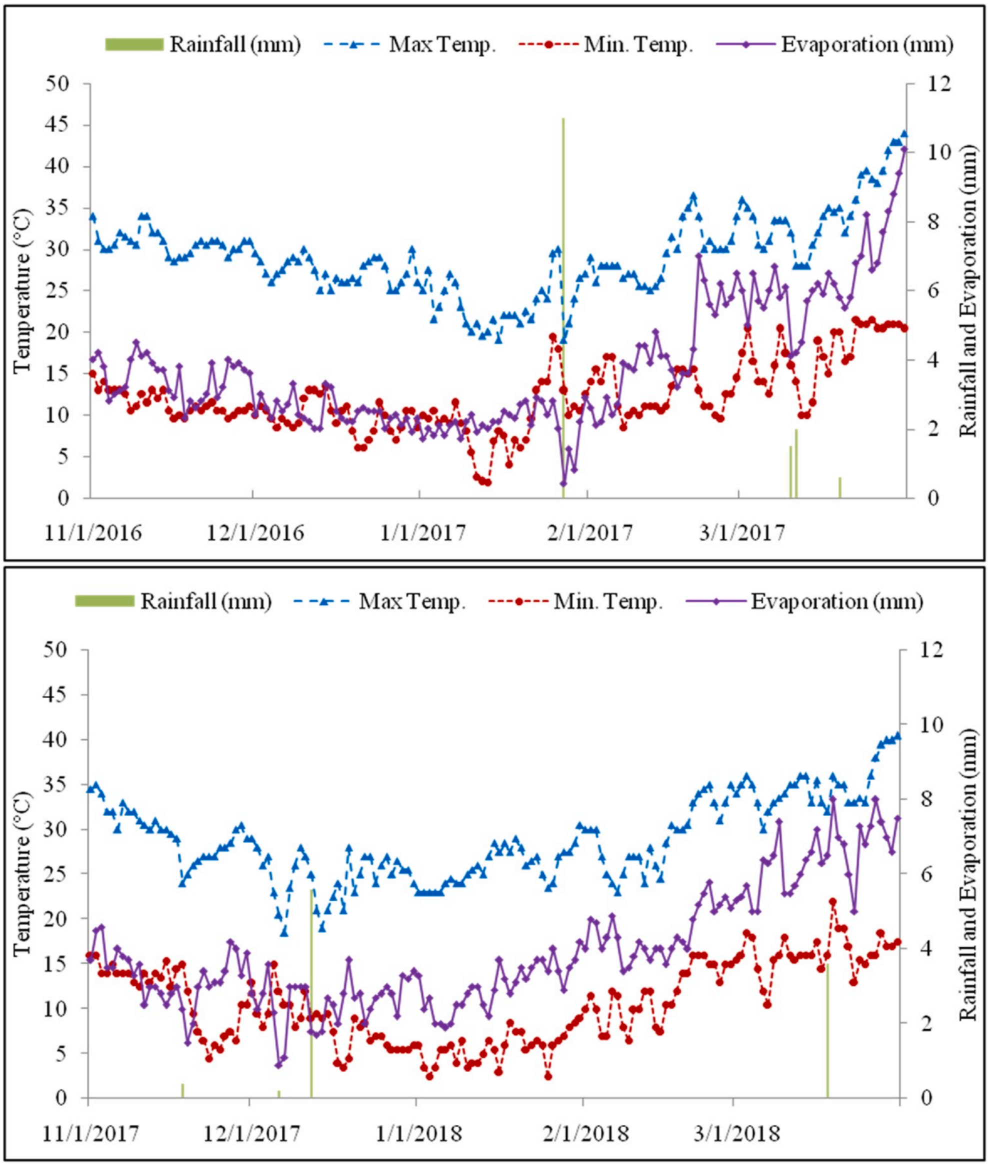

Fig. 1. Daily weather parameters during 2016–17 and 2017-18 years of experimentation, primary axis represents the maximum and minimum temperature and secondary axis represents the rainfall and evaporation recorded during the crop growing period.

effectively and reduces run off of contaminants such as pesticides.

Therefore, use of waste wool as manure can be a solution for recycling and safe disposal of large quantities of waste wool. Water conservation properties of waste wool may also be helpful in beneficial crop production under low rainfall or water deficit areas. Keeping the above facts in mind we have made efforts for utilization of waste wool in agriculture field and its safe disposal by composting it for 2–3 years. A series of small experiments have been conducted with encouraging results in terms of moisture retention in field and better biomass accumulation in crops (Kadam et al., 2013). To move a step forward, bulk waste wool was collected and manure was prepared with waste wool, sheep manure and crop residues in ratio of 30:50:20 and named as Avikhad. The present study was planned with the hypothesis that use of waste wool in agricultural field can be a safe disposal option and byproduct recycling along with integration of sheep rearing with crop production system. The objectives of the study were 1) to explore the way of safe disposal of waste wool in crop production and its comparison with organic amendments, 2) to study the effect of sheep based organic waste on soil health, crop productivity and quality under normal irrigation and water deficit conditions, and 3) to find out whether use of waste wool as manure results in appreciation or depreciation of the system. The study is novel as in India it is the first time when effect of waste wool as such has been studied comprehensively on overall soil health, crop productivity and water use along with comparable properties of its manure.

2. Materials and methods

2.1. Experimental setup

To fulfill the aforesaid objectives, the experiment was conducted at ICAR-Central Sheep & Wool Research Institute, Avikanagar (75^0-28′E longitude, 26^0-26′N latitude and 320 m altitude), in semiarid regions of Rajasthan. In general, weather conditions were stable but was more favorable during 2017–18 years of study; maximum temperature varied from 19 to 44 °C (average 29.1 °C) in 2016–17 and 21–40.5 °C (average 28.9 °C) in 2017–18 whereas, minimum temperature ranged from 1.8 to 21.5 °C (average 12.1 °C) in 2016–17 and 2.5–19 °C (average 10.6 °C) in 2017–18. Rainfall received was 15.1 and 9.8 mm in 2016–17 and 2017–18, respectively; evaporation rate (3.7 and 3.9 mm in 2016–17

Table 1
Physico-chemical properties of soil and organic waste used in the experiment.

Parameters	Soil	Sheep manure	Wool manure/ Avikhad	Waste wool-1	Waste wool-2
Sand (%)	72.3	–	–	–	–
Silt (%)	15.1	–	–	–	–
Clay (%)	12.6	–	–	–	–
Carbon	0.27 (OC in %)	20.8 g kg^{-1}	14.72 g kg^{-1}	276 g kg^{-1}	283 g kg^{-1}
pH	7.9	7.8	7.2	6.8	6.8
EC (ds m^{-1})	0.221	ND	ND	ND	ND
Bulk density (g cc^{-1})	1.64	1.17	0.92	0.52	0.50
C: N ratio	NA	13.6	18.8	3.65	3.71
N	138 kg ha^{-1}	1.48%	0.78%	144 g kg^{-1}	146 g kg^{-1}
P	11.1 kg ha^{-1}	0.57%	0.69%	609 mg kg^{-1}	611 mg kg^{-1}
K	183 kg ha^{-1}	1.31%	3.4%	30.1 g kg^{-1}	32.5 g kg^{-1}
Ca	2.4 g kg^{-1}	3.3%	ND	1.07 g kg^{-1}	1.09 g kg^{-1}
Mg	1.8 g kg^{-1}	0.8%	ND	339 mg kg^{-1}	344 mg kg^{-1}
S	10.67 g kg^{-1}	1.48 g kg^{-1}	ND	49.7 g kg^{-1}	50.8 g kg^{-1}
Cu	0.67 mg kg^{-1}	0.56 mg kg^{-1}	ND	5.62 mg kg^{-1}	5.83 mg kg^{-1}
Zn	0.71 mg kg^{-1}	0.72 mg kg^{-1}	ND	466 mg kg^{-1}	479 mg kg^{-1}
Fe	4.36 mg kg^{-1}	2.89 mg kg^{-1}	ND	232 mg kg^{-1}	240 mg kg^{-1}
Mn	19.67 mg kg^{-1}	5.45 mg kg^{-1}	ND	14.2 mg kg^{-1}	16.8 mg kg^{-1}

OC: organic carbon; EC: electrical conductivity; ND: not detected; C: N carbon: nitrogen; N: nitrogen; P: phosphorus; K: potassium; Ca: Calcium; Mg: Magnesium; S: Sulphur; Cu: copper; Zn: zinc; Fe: iron; Mn: manganese.

and 2017–18) remained stable (Fig. 1). The experiment was conducted under natural day/night conditions during the Rabi season in iron containers (19 cm diameter) containing 50 kg sandy loam soil per pot, soil properties are given in Table 1. The experiment was arranged in factorial randomized block design with six replications. In the treatments, different combinations of irrigation water/cumulative pan evaporation (IW/CPE) ratio for irrigation and manures were considered. Two IW/CPE ratios were kept i.e. 1.0 (normal) and 0.67 (slight deficient); and five different manure were used i.e. control, sheep manure, wool manure (Avikhad), Waste wool 1 and 2. Sheep manure used was natural and untreated; wool manure was prepared with mixing of waste wool, sheep manure and crop residues in ratio of 30:50:20. Waste wool consisting of impurities and dirt just after shearing was designated as waste wool 1 and after removal of impurities was designated as waste wool 2. The physico-chemical properties of these manures and waste wool are presented in Table 1. Ten healthy grains of barley were sown in each pot after surface sterilization with 0.001(M) $HgCl_2$ solution and washing thoroughly with distilled water. Fifty percent of recommended doses of nitrogen, phosphorus and potassium (N, P and K) fertilizers were applied in addition to organic wastes as per treatments except control.

2.2. Analysis of soil samples and organic amendments

Representative soil samples (0–15 cm) were collected at the initiation and completion of experiment. For analyzing physical and chemical properties of soil, samples were dried, ground and sieved with 2 mm sieve. Bouyoucos hydrometer method was used for soil texture estimation. For estimating soil organic carbon (SOC) elemental analyzer was used, available N, P and K in soil were determined by following the procedures of Subbiah and Asija (1956), Bray and Kurtz (1945) and Piper (1966), respectively. The micronutrients in soil i.e. iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) were analysed by tri-acid digestion and Diethylenetriamine pentaacetate (DTPA) extraction in Atomic absorption spectroscopy (AAS) as per Lindsay and Norvell (1978), whereas, in organic amendments samples, for determining micronutrients digestion was done by $HClO_4$+HNO_3. The pH, electrical conductivity (EC) and organic carbon (OC) of organic materials were measured like soil; total nitrogen (N) and phosphorus (P) were measured colorimetrically after the digestion of organic materials in 1.2:1 H_2SO4: H_2O_2 mixture at 360 °C. Soil enzymes i.e, dehydrogenase (DHA), urease, β-glucosidase, acid and alkaline phosphatase were estimated by following the procedures of Tabatabai (1994) and Dick et al. (1996), whereas, for determining the activity of Fluorescein diacetate (FDA) protocol of Adam and Duncan (2001) was followed.

2.3. Growth, yield attributes and yield

Destructive sampling of plants was done and leaf area was measured by taking length and breadth of individual leaf and total number of leaves per plant was counted and then leaf area index (LAI) was calculated. After leaf area measurement plant samples were dried at 65 °C temperature in oven for recording the constant dry weight and converted into dry matter accumulation (g/plant). Crop growth rate (CGR), relative growth rate (RGR) and net assimilation rate (NAR) was computed with the given equations:

$$LAI = \frac{\text{Total leaf area of the crop (cm2)}}{\text{Total land area under the crop (cm2)}} \quad (1)$$

$$CGR\ (mg / plant / day) = \frac{W2 - W1}{T2 - T1} \quad (2)$$

$$RGR\ (mg / g / day) = \frac{\text{Log } W2 - \text{Log } W1}{T2 - T1} \quad (3)$$

$$NAR(g / day / plant) = \frac{(W2 - W1)\ (\ln LA2 - \ln LA1)}{(T2 - T1)\ (LA2 - LA1)} \quad (4)$$

where, W_1 and W_2 are plant dry weights at time T_1 and T_2, respectively and LA_1 and LA_2 are the leaf area values at time T_1 and T_2, respectively under natural logarithm.

At the time of harvesting, tillers were counted randomly from each treatment, length and weight of earheads was determined. Grains were counted with the help of grain counter from five random earheads and 1000 grains were weighed for recording test weight. The crop was harvested, threshed and yields were recorded. Harvest index was calculated as the ratio of grain yield to biological yield (grain + straw yield).

$$Harvest\ index = \frac{economic\ yield\ (grain\ yield)}{Biological\ yield} \times 100 \quad (5)$$

2.4. Bulk density, soil porosity, consumptive use of water and water use efficiency

Soil bulk density was determined by removing a block of soil from 0 to 15 cm soil depth with the help of core sampler and expressed as g/cc. Porosity of soil was calculated by Percentage of the bulk volume not occupied by Solids (Casanova et al., 2016). For water studies a measured quantity of water was applied for irrigation as per the treatments. For determining soil moisture deficit (60 cm soil depth) the method of Dastane (1972) was followed. The difference in soil moisture before applying water and after irrigation was considered as actual soil moisture deficit. To work out the consumptive use, a measured amount of water was added to every container and the amount of applied water was summed at harvest. Soil sampling was done immediately after sowing and continued up to harvesting, samples were taken just before

Table 2
Effect of sheep based organic waste and irrigation schedules on chemical properties of soil after 2 years of experimentation in barley.

	pH	OC (%)	N	P	K	Fe	Cu	Zn	Mn
			kg ha^{-1}			mg kg^{-1}			
Irrigation schedules									
IW/CPE ratio 1.00	7.4a	0.33a	168a	14.6a	211a	4.76a	0.73a	0.86a	22.2a
IW/CPE ratio 0.67	7.6a	0.28 b	164a	13.3a	203a	4.69a	0.67a	0.81a	21.1a
Organic waste									
Control	7.7a	0.26 b	135c	10.5 b	181c	4.42c	0.64 b	0.69c	19.3c
Sheep Manure	7.6a	0.30 ab	167 b	14.2a	209 b	4.79 b	0.75a	0.79 ab	21.3 b
Avikhad	7.4 ab	0.32a	171 b	14.8a	212 ab	4.86 ab	0.78a	0.85 ab	22.2a
Waste wool-1	7.2 b	0.34a	178a	15.2a	216a	4.89a	0.80a	0.91a	22.7a
Waste wool-2	7.2 b	0.34a	179a	15.2a	217a	4.90a	0.80a	0.92a	22.7a

N: nitrogen; P: phosphorus; K: potassium; Cu: copper; Zn: zinc; Fe: iron; Mn: manganese; The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

irrigation and 24 h after irrigation from 0 to 15 and 15–30 cm soil depth into aluminium soil moisture boxes, initial weight of (W_1) boxes was immediately taken after sampling and then boxes were kept in oven and dried at 105 °C till constant dried weight (W_2) was obtained. The loss in moisture was calculated as:

$$\text{Soil moisture content}(\%) = (W1 - W2)/W2 \times 100 \tag{6}$$

The data obtained on moisture percentage for each depth was used for calculating profile soil moisture use (depletion) and consumptive use

$$(\text{CU})\ d = \sum_{i=1}^{n} \frac{M_1^i - M_2^i}{100} \times BDi \times Di \tag{7}$$

where, CU is consumptive use of water, d is the moisture depletion at the root zone of crop, M_1^i and M_2^i are the soil moisture (%) in the ith soil layer after 1day of irrigation and on the day before next irrigation, BD is bulk density and D is soil depth.

$$CU = \sum_{i=1}^{n} (\text{bj} + \text{ej}) + \text{ER} \tag{8}$$

where, bj and ej are the moisture content of profile at beginning and end of jth interval, n is the total time interval during which water is applied and Eris the effective rainfall in mm.

$$\text{WUE}\ \ (\text{kg}/\text{ha} - \text{cm})\ \ = (\text{Grain yield}\ \ (\text{kg}/\text{ha}))/(\text{Consumptive use}\ \ (\text{cm})) \tag{9}$$

where, WUE is water use efficiency.

2.5. Fodder quality parameters

The barley plant samples were collected at full bloom stage and analysed for dry matter (DM) content by drying at 70 °C till constant weight. The samples were processed and analysed for ash, crude protein and ether content by standard protocol of AOAC (2000). Fiber fractions i.e, acid and neutral detergent fiber was determined as per Van Soest et al. (1991) whereas, lignin content was estimated by the procedure of Robertson and Van Soest (1981).

2.6. Statistical analysis

The experimental data pertaining to plant, water use and soil physico-chemical properties were subjected to analysis of variance (ANOVA) for factorial randomized block design using SAS 9.3 software. When F value was significant, least significant difference (LSD at 5% level of significance) values were used to compare the treatment means. The results are presented at 5% level of significance (P = 0.05). The principal component analysis (PCA) was performed in XLSTAT software.

3. Results

3.1. Soil health

The initial soil properties and characteristics of different organic amendments used as manure in the experiment are presented in Table 1. The experimental soil was slightly alkaline with pH 7.9, texture was sandy loam, and soil is low in available nitrogen (N) whereas, medium in organic carbon (OC), available phosphorus (P) and potassium (K), overall status of soil fertility is poor. pH of sheep manure is alkaline but waste wool and Avikhad was neutral in nature having pH of 6.8 and 7.2. Both types of waste wool had higher concentration of carbon (C), N, K, sulphur (S) and other micronutrients as compared to other manures

Table 3
Effect of sheep based organic waste and irrigation schedules on soil enzymatic activities after 2 years of experimentation in barley.

	Acid Phosphatase (μg g^{-1} soil hr^{-1})	Alkaline Phosphatase (μg g^{-1} soil hr^{-1})	DHA (μg TPF g^{-1} d^{-1})	FDA (μg of fluroscein g-1 soil h^{-1})	Urease (μg g^{-1} soil)	β-glucosidase (μg p-nitrophenol g^{-1} d^{-1})
Irrigation schedules						
IW/CPE ratio 1.00	48.1a	42.2a	54.8a	1.82a	142.5a	26.3a
IW/CPE ratio 0.67	38.2 b	30.7 b	46.1 b	1.52 b	122.1 b	21.7 b
Manure application						
Control	36.5 b	30.1c	44.3c	1.47c	123.2 d	20.5c
Sheep Manure	43.5a	34.6 b	48.1 b	1.59 b	129.4c	21.3c
Avikhad	44.9a	38.1a	52.6 ab	1.72a	134.6 b	24.2 b
Waste wool-1	45.2a	39.5a	53.4a	1.78a	136.7a	26.9a
Waste wool-2	45.4a	39.7a	53.9a	1.79a	137.1a	27.1a

DHA: dehydrogenase; FDA: Fluorescein diacetate; The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

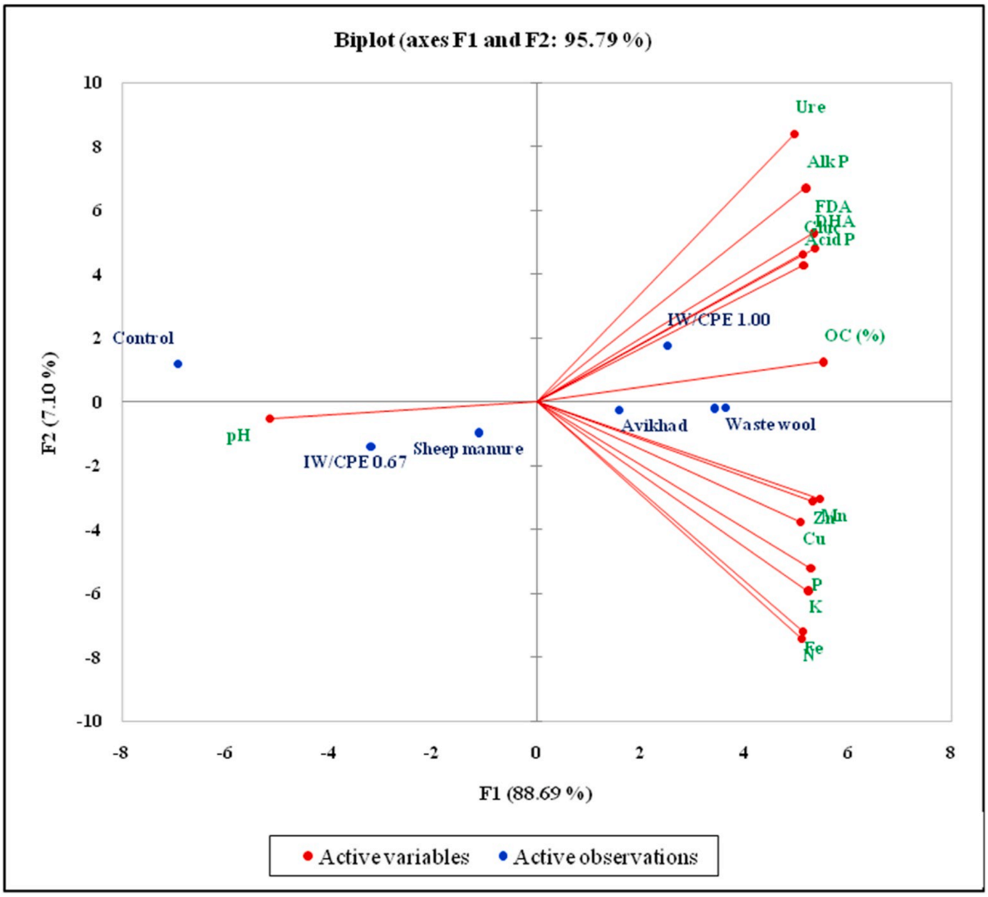

Fig. 2. Principal component analysis ordination diagram of soil quality parameters and different treatments of the study.

Table 4
Results of principal component analysis (PCA) of soil health indicators.

Principal components	PC1	PC2	PC3
Eigen value	13.303	1.065	0.429
% of total variance	88.686	7.101	2.857
Cumulative %	88.686	95.787	98.644
Factor loadings/Eigen vectors			
pH	−0.925	−0.027	0.365
OC (%)	0.995	0.064	−0.043
N	0.920	−0.378	0.022
P	0.952	−0.266	0.141
K	0.943	−0.302	0.118
Fe	0.925	−0.366	0.084
Cu	0.916	−0.192	0.018
Zn	0.958	−0.160	−0.206
Mn	0.983	−0.155	−0.020
Acid Phosphatase	0.926	0.218	0.306
Alkaline Phosphatase	0.934	0.341	0.106
Dehydrogenase	0.965	0.245	0.019
FDA	0.962	0.269	−0.013
Urease	0.894	0.428	0.135
β-glucosidase	0.924	0.236	−0.293

indicating waste wool as enriched organic amendment. It also had narrow carbon: nitrogen (C: N) ratio making it easy and fast decomposing manure for good fertilization.

The byproducts of sheep farming were tested as organic amendment and compared with other waste wool in barley at two IW/CPE ratios. The initial pH of the soil was alkaline, and after 2 years of experimentation, it shifted towards neutral side with the application of waste wool (Table 2). The most significant effect of waste wool in soil was build up of organic carbon and increase in concentration of N. Though overall fertility status of soil was improved by use of wool waste, like P, K, Fe, Cu, Zn, Mn, but significant improvement was observed in OC and N, which was around 30.8 and 32.6% over control; 9.7 and 5.9% over combined sheep and wool manure, respectively (Table 2). The IW/CPE ratios did not have any significant effect on fertility status of soil.

All the organic amendments have significant positive effect on soil enzymatic activity and results were more promising with waste wool application and followed the trend as waste wool > wool manure > sheep manure > control (Table 3). The activities of DHA, FDA, Urease, and phosphatase enzymes were 11–27% and 3–7% higher in waste wool treatment over control and sheep based manures, respectively, whereas activity of β-glucosidase was 32 and 19% higher with waste wool application. All the soil enzymes were significantly higher in normal irrigated conditions i.e. IW/CPE ratio 1.0. Based on the variation present in all soil quality parameters among different treatments, they were further analysed by PCA and depicted in Fig. 2. The total variation in the principal axes 1 and 2 was around 88.7 and 7.1%, respectively (cumulative value = 95.8%). Two principal components (PCs) had Eigen values > 1 that explained 96% and 4 PCs having Eigen values around 0.4 that explained 98% of variation in the data (Table 4). Among all parameters OC has the highest factor loading. All the parameters were explained towards positive side except pH. The PCA ordination diagram demonstrated some significant associations, in particular all the enzymes were more governed by the IW/CPE ratio rather than manuring treatments and among organic wastes, waste wool and wool manure/Avikhad controlled all the soil quality parameters.

3.2. Forage productivity and quality

Growth, yield and quality of barley were significantly affected by the addition of different organic manures and IW/CPE ratio of irrigation. To

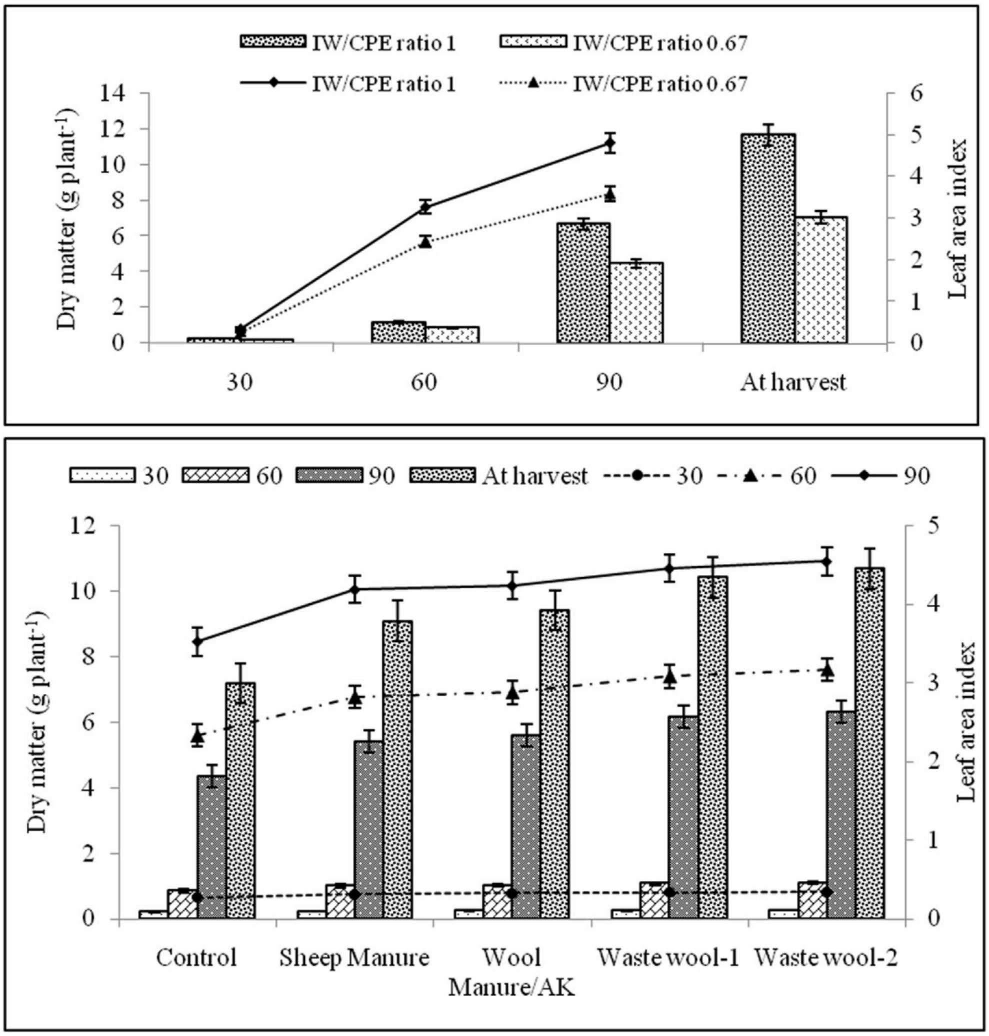

Fig. 3. Effect of irrigation schedules and sheep based organic waste on dry matter accumulation (g plant^{-1}) and leaf area index recorded at periodical intervals of the barley, primary axis represents the dry matter accumulation of barley and lines on secondary axis represents the leaf area index (vertical bars in each column and each line represent standard error).

observe the effect of manures, different growth parameters were recorded periodically, i.e. dry matter, LAI, CGR, RGR and NAR. Deviation from the normal irrigation to slight stress led to the reduction in growth of all parameters. The dry matter and LAI was significantly higher when waste wool was applied as manure, though the difference in waste wool 1 and 2 was not significant, and the biomass accumulation was lowest in control (Fig. 3). Waste wool application has resulted in around 46.8, 16.2, and 12.1% increase in biomass production of barley over control, sheep and wool manure, respectively. The CGR, RGR and NAR were also governed by dry matter production so, they also followed the trend as waste wool > wool manure > sheep manure > control (Figs. 4–6). Moreover, favorable weather during 2018 resulted in better growth and production of forage as compared to 2017. Length of earhead was the most affected parameter due to moisture stress (IW/CPE 0.67) followed by 1000 seed weight. Like growth parameters, yield attributes were significantly higher in waste wool treatment during both the years, and slight variation was recorded among other treatments. Number of effective tillers, number of grains, weight of earhead and test weight of barley was 27.8, 15.4, 19.5 and 8.3% higher with waste application as compared to control, respectively (Table 5). Better growth parameters led to better yield attributes and they resulted in better yield, as with waste wool application and under normal irrigated conditions. Irrigating the crop at IW/CPE 0.67 reduced the crop yield by 48% leading to 14.3% lower harvest index, irrespective of the years. Among the manuring treatments, waste wool produced 51.2, 17.1 and 13.5% higher grain yield over control, sheep manure and wool manure, respectively (Table 6). Although, the difference in waste wool 1 and waste wool 2 was non-significant but the yield was apparently higher in waste wool 2 (2.9%). The dry fodder yield was 53.2% higher with waste wool application over control.

For assessing the fodder quality, dry matter, crude protein, fibre content, ether and ash content were quantified and all the quality parameters were significantly affected by application of organic amendments, especially waste wool. Waste wool application favors palatability and digestibility of fodders due to high crude protein (CP), ether extract (EE) and low crude fiber (CF) and acid detergent fiber (ADF), whereas the content of fiber and lignin was higher in control. The increase in dry matter and crude protein content was around 14 and 13% with waste wool application as compared to control. The ether extract and ash content was also increased significantly with all the organic fertilizers by around 14.1–25.8% and 4.3–17.4%, respectively over control. Waste wool manuring not only enhanced the crude protein and dry matter but also reduced the crude fiber by 14.7% and acid detergent fiber by 10.9% indicating the better forage quality of barley (Table 7). However, fodder quality remained unaffected with waste wool 1 and 2. The water stress conditions significantly reduced the CP and DM by 9–10%, and increased the content of CF (by 15%), ADF (up to 11.9%) and NDF (by 4.8%), suggesting stress conditions were harmful not only for yield but

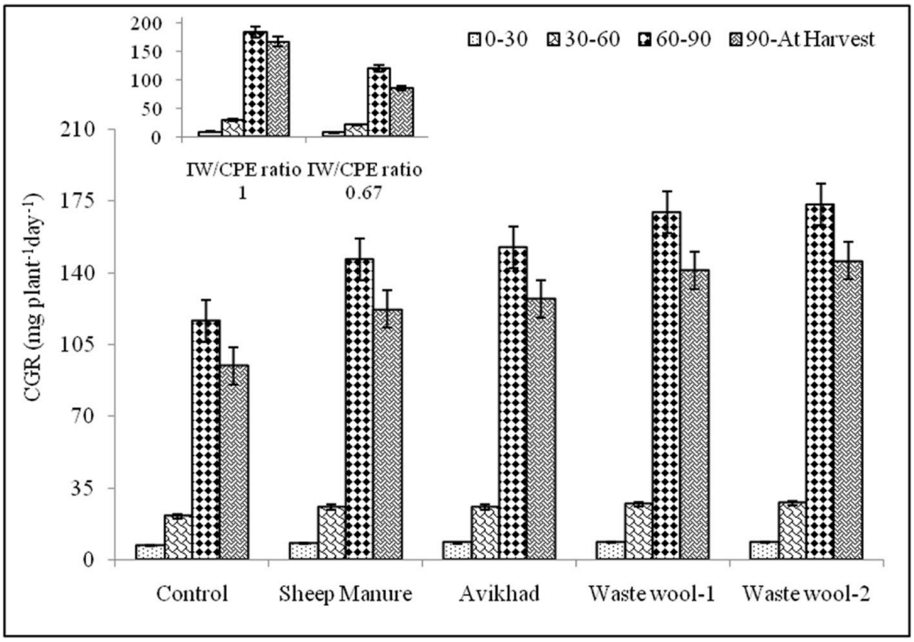

Fig. 4. Effect of irrigation schedules and sheep based organic waste on crop growth rate (mg plant^{-1} day^{-1}) recorded during periodical intervals (sowing to harvest) of the barley, (vertical bars in each column represent standard error).

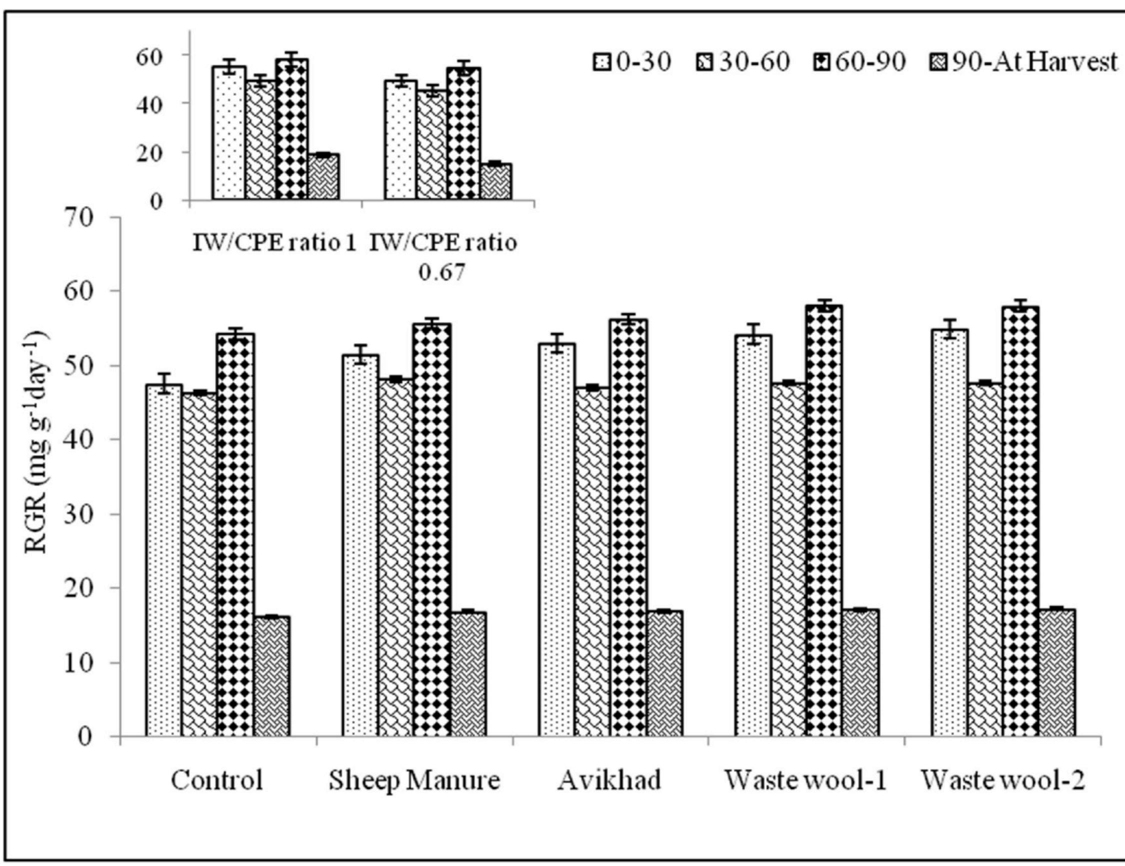

Fig. 5. Effect of irrigation schedules and sheep based organic waste on relative growth rate (mg g $^{-1}$ day^{-1}) recorded during periodical intervals (sowing to harvest) of the barley, (vertical bars in each column represent standard error).

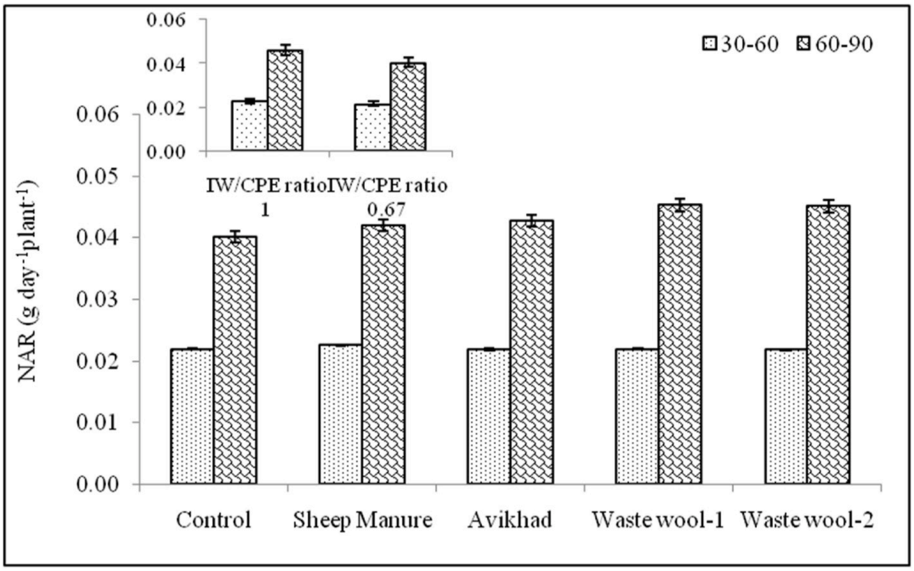

Fig. 6. Effect of irrigation schedules and sheep based organic waste on net assimilation rate (g $^{-1}$ day^{-1} plant^{-1}) recorded during periodical intervals (sowing to harvest) of the barley, (vertical bars in each column represent standard error).

Table 5
Effect of sheep based organic waste and irrigation schedules on yield attributes of barley.

	Plant height (cm)		Effective tillers plant^{-1}		No. of grains earhead^{-1}		Weight of earhead (g)		Length of earhead (cm)		1000-seed weight (g)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Irrigation schedules												
IW/CPE ratio 1.00	75.3a	79.0a	3.48a	3.53a	45.2a	46.5a	1.96a	1.97a	8.33a	8.39a	43.6a	43.7a
IW/CPE ratio 0.67	63.2 b	66.4 b	2.34 b	2.37 b	36.4 b	37.5 b	1.50 b	1.52 b	5.72 b	5.75 b	36.5 b	36.6 b
Manure application												
Control	63.5 b	66.7 b	2.46c	2.51c	37.2c	38.3c	1.54c	1.55c	6.19c	6.27c	38.0 b	38.1 b
Sheep Manure	69.2a	72.6a	2.87 b	2.92 b	40.4 b	41.4 b	1.71 b	1.72 b	7.04 b	7.07 b	39.9 ab	39.9 ab
Avikhad	70.0a	73.5a	2.92 ab	2.95 ab	40.7 b	41.9 b	1.74 b	1.74 b	7.08 b	7.14 b	40.1a	40.3a
Waste wool-1	71.4a	74.9a	3.14a	3.17a	42.8a	44.1a	1.81a	1.83a	7.38a	7.39a	40.9a	41.0a
Waste wool-2	72.1a	75.7a	3.17a	3.20a	43.1a	44.4a	1.85a	1.88a	7.44a	7.48a	41.3a	41.4a

The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

Table 6
Effect of sheep based organic waste and irrigation schedules on grain and fodder yield of barley.

	Grain yield (g plant^{-1})				Dry fodder yield (g plant^{-1})			
	2017		2018		2017		2018	
	IW/CPE ratio 1	IW/CPE ratio 0.67	IW/CPE ratio 1	IW/CPE ratio 0.67	IW/CPE ratio 1	IW/CPE ratio 0.67	IW/CPE ratio 1	IW/CPE ratio 0.67
Control	5.28	2.50	5.28	2.58	11.81	6.72	11.81	6.88
Sheep Manure	6.65	3.41	6.67	3.41	14.70	8.75	14.73	8.75
Avikhad	7.01	3.46	7.01	3.46	15.46	8.82	15.48	8.82
Waste wool-1	7.46	4.16	7.53	4.16	16.37	10.51	16.46	10.51
Waste wool-2	7.77	4.21	7.80	4.21	17.00	10.56	17.06	10.56
$LSD_{P=0.05}$	0.49		0.51		0.78		0.83	

The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

for quality.

3.3. Water use

Water parameters were mainly influenced by irrigation of crop at different IW/CPE ratios, and water use efficiency (WUE) at 0.67 IW/CPE ratios was reduced by 43% as of normal irrigated crop. Addition of all organic amendments significantly improved the consumptive use (CU), rate of moisture use and WUE (Table 8). Sheep based manures had more promising results over waste wool in terms of water use by the crop during both the years. By addition of sheep and wool manure, consumptive use and rate of moisture use was enhanced by 2.2 and 1.8% over control, respectively. Water use efficiency was governed by yield; therefore, WUE was higher with waste wool application (33.5% over control). Addition of all organic wastes improved the soil physical properties related to moisture retention like bulk density (BD), porosity and range of available soil moisture in same soil. Their addition decreased the BD, increased porosity, field capacity and permanent wilting point, and the results obtained followed the trend as sheep manure > wool manure/Avikhad > waste wool > control (Table 9). The improvement in physical properties led to better CU and moisture use with the addition of organic waste especially sheep manure.

Table 7
Effect of sheep based organic waste and irrigation schedules on fodder quality of barley.

	DM (%)	CP (%)	EE (%)	CF (%)	ADF (%)	NDF (%)	Ash (%)
Irrigation schedules							
IW/CPE ratio 1.00	24.19a	12.78a	6.67a	12.62 b	27.69 b	58.7a	3.57a
IW/CPE ratio 0.67	22.06 b	11.63 b	5.50 b	14.51a	30.99a	61.5 b	3.43a
Manure application							
Control	21.07c	11.25 b	5.19c	14.91a	31.4a	61.9a	3.28c
Sheep Manure	22.54 b	12.02a	5.92 b	13.75 b	29.6 b	59.9 b	3.42 b
Avikhad	23.17 b	12.38a	6.27 b	13.16 b	29.1 b	59.2 b	3.59 b
Waste wool-1	24.38a	12.67a	6.49a	13.06 b	28.3 b	57.8c	3.78a
Waste wool-2	24.45a	12.69a	6.53a	13.01 b	28.3 b	57.8c	3.85a

DM-dry matter; CP-crude protein; EE-ether extract; CF-crude fiber; ADF-acid detergent fiber; NDF-neutral detergent fiber; The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

Table 8
Effect of sheep based organic waste and irrigation schedules on consumptive use, rate of moisture and water use efficiency after 2 years of experimentation in barley.

	Consumptive use (mm)		Rate of moisture use (mm-day^{-1})		Water use efficiency (kg-ha^{-1} cm^{-1})	
	2017	2018	2017	2018	2017	2018
Irrigation schedules						
IW/CPE ratio 1.00	398.8a	390.8a	3.2a	3.2a	152.2a	155.9a
IW/CPE ratio 0.67	298.3 b	290.3 b	2.4 b	2.4 b	105.7 b	109.0 b
Organic waste						
Control	343.6c	335.6c	2.75c	2.73c	97.7c	101.1c
Sheep Manure	351.8a	343.8a	2.81a	2.80a	123.7 b	126.8 b
Avikhad	350.2 ab	342.2 ab	2.80 ab	2.78 b	129.0 b	132.0 b
Waste wool-1	348.5 b	340.5 b	2.79 b	2.77 b	145.0a	149.2a
Waste wool-2	348.5 b	340.5 b	2.79 b	2.77 b	149.4a	153.1a

The mean values with the same letter in column are not significantly different at the 5% level of significance using Duncan's multiple Range Test (DMRT).

4. Discussion

Waste wool surplus is also an organic waste, which is not useful for sheep farmers because of lack of demand and therefore, it is no longer a commercial viable product and its safe disposal is essential for the benefits of farmers and consumers (Zheljazkov, 2005), its use as manure in soil can be a viable option (Sharma et al., 2019). Utilization of protein-rich product such as waste wool and other organic by-products of sheep would offer additional advantages of waste reduction, resources conservation, and economic advantages to industries as well as sheep farmers. Waste wool have higher content of C and N than the rest used organic manures, so, its disposal in soil for agriculture production may be good option for its use as a fertilizer apart from safe disposal. Sheep wool is made up of keratin (protein) and contains an adequate amount of essential plant nutrients viz., N, C and S (Górecki and Górecki, 2010), K, Na, P, Mg, Fe, Mn, and Zn (Zheljazkov et al., 2008) and it can be a more balanced organic fertilizer for plants.

4.1. Effect of sheep based organic waste on soil health and water use

Incorporation of waste wool in soil improves water holding capacity, decomposes slowly and releases nutrients for crop plants and acts as a slow-release fertilizer (Zheljazkov, 2005; Górecki and Górecki, 2010). After one growing season soil contain abundance of easily accessible mineral compounds and organic un-decomposed particles that become a rich source of nutrients for the succeeding crop (Kadam et al., 2013). In our study, waste wool application neutralized the soil pH and improved overall soil fertility, but significant effect was build up of organic carbon and increase in concentration of N. This improvement may be due to decomposition of organic matter (OM), which releases nutrients through mineralization and stimulates soil enzymatic activities. Soil enzymatic activities are the reflection of the effects of cultivation, soil properties and pedological amendments and are used as indicators of soil fertility (Shahid et al., 2016). In the study, the activities of all the soil enzymes were 10–30% higher under waste wool treatment over control. Soil enzymatic activities was considerably lower in water stress condition might be due to the fact that living biota of soil was more affected by altering soil environment and lack of moisture slows down the enzyme activity and microbial growth. Voncina and Mihelic (2013) and Suruchi et al. (2014) also reported that soil fertility was enhanced by application of wool waste, as it added ammonium-nitrogen (NH_4–N) and nitrate-nitrogen (NO_3–N), which increased the total N and improved the microbial properties of soil. The addition of waste wool can improve crop production in arid and semiarid regions as soil of these regions are alkaline in nature and sheep wool hydrolyzate contains N and S compounds and their oxidation and mineralization leads to reduction in soil pH (Tiwari et al., 1989); therefore, waste wool provides better growing conditions for crop plants by supplying essential nutrients like N, C, and P in the soil (Govi et al., 1998). Saha et al. (2008) and Scotti et al. (2015) reported that application of organic amendments to soil provided a better potential for higher enzyme activities mainly by increasing microbial biomass, organic carbon and organic matter contents in soil, however, the response of enzyme activities varied according to organic amendment nature.

Waste wool is very light and less dense (Shanumugam and Jose, 2019), which may reduce soil bulk density and enhance porosity of the soil (Abdallah et al., 2019). In our study, organic manures significantly improved the water use, and promising results were obtained with sheep manure, however, the water use efficiency, which was regulated by yield, was significantly higher with waste wool. Moisture retention in soil and water use by crops largely depends on pore size and particle-size distribution, which was governed by soil structure, texture, bulk density, OC content (Pollacco, 2008) and crop cultivated. Organic matter application has multiple effects like improving soil water holding

Table 9
Available soil moisture range (ASM) of soil as affected by different organic waste.

Organic manures	Bulk Density	Porosity (%)	Field Capacity (%)	Permanent Wilting Point (%)	Available Soil Moisture (%)	% change compare to control in ASM
Control	1.58	40.38	19.58	8.38	11.20	–
Sheep Manure	1.53	42.26	21.37	8.40	12.97	15.80
Avikhad	1.54	41.96	21.00	8.40	12.60	12.50
Waste Wool-1	1.55	41.70	20.73	8.39	12.34	10.18
Waste Wool-2	1.55	41.51	20.72	8.39	12.33	10.09

capacity, but hydrophilic or hydrophobic nature of OM also governs soil water retention (Bachmann et al., 2007; Sharma et al., 2019). de Melo et al. (2019) reported that organic matter in soil regulates soil water dynamics by enhancing soil properties like permeability, porosity and water holding capacity and further promotes soil biological activity. It was also reported that when sandy soils treated with organic matter like carpet wool waste, reduced the nutrient leaching by ceasing water movement leading to better crop production (Mubarak et al., 2009). Scotti et al. (2015) reported the addition of organic amendment increases 25–36% organic matter content in soil which reduces the compactness (bulk density) by improving aeration (porosity), water permeability and water holding capacity of soil.

4.2. Effect of sheep based organic waste on growth, quality and productivity of barley

The recycling of organic wastes in agriculture can be an important step for sustaining soil health and protecting the environment from unwanted hazards apart from supplying essential plant nutrients. McNeil et al. (2007) found that carpet wool after grinding can be successfully used as fertilizer for Italian ryegrass (*Lolium multiflorum*) cultivation. According to Choudhary et al. (2018), application of wool waste as a nutrient source for field crops may be an excellent soil amendment for improving yield and quality of produce. In this study, yield was increased significantly with all organic fertilizers, but waste wool contributed the most i.e. around 50% higher grain yield and 53% higher fodder yield was produced as compared to control. All the growth parameters and yield contributing characters were also improved with waste wool. The water stress given to crop also reduced the yield and yield parameter, length of earhead was the most affected character due to water stress. Several researchers were also reported that substrate amendment with waste wool as fertilizer source contributed to taller plants, higher biomass of plants and greener appearance of leaves (LAI) led to a significant increase in yield and quality of crops (McNeil et al., 2007; Zheljazkov et al., 2009; Górecki and Górecki, 2010). Further, it was observed that vegetation period of the crop was prolonged leading to delayed aging. Bőhme et al. (2008) also successfully cultivated cucumbers in slabs of manure consisting sheep wool and coconut fiber, crop grown in wool containing slabs yielded 19–42% more than those cultivated in coconut fiber slabs. In our study, fodder quality was greatly improved by application of sheep based organic wastes especially waste wool. Abdalla et al. (2007) also reported that supply of nitrogen through organic wastes has been resulted in increase in higher crude protein content. Further, Ahmad et al. (2012) also reported that application of organic manures improved the nutrient availability and uptake which builds up amino acids and phosphorus content, which might have contributed to large photosynthetic activity and higher synthesis of protein in fodder. The use of a waste wool as a fertilizer for food crop production may be questioned because of issues like marketability and social acceptance.

5. Conclusions

The utilization of waste wool in crop production can be an opportunity in two ways i.e. a safe disposal of waste wool and potential fertilizer for better crop productivity and quality. The use of organic waste as manure upgrades the soil health by improving soil properties and microbial activity. The use of all organic amendments significantly increased yield and quality of barley forage by improving the soil properties and crop water use. The results were more promising under waste wool, even under water deficit conditions. Although it is a new concept and needs further research on its impact on crop, soil, food and humans before any concrete recommendation and for that new scientific development needs to be explored. Further studies are required for developing the application rates of waste wool according to crop and region along with their nutrient release dynamics so that nutrient supply will synchronise with the demand of plant and availability will be higher with lesser nutrient loss.

Author contribution statement

B Lal, SC Sharma and RL Meena: Conceptualization; Formal analysis; Investigation; Methodology; Project administration. Priyanka Gautam and Srobana Sarkar: Data analysis and writing. A Sahoo: Project administration. BP Meena and Roop Chand: Analysis and Validation

Declaration of competing interest

On behalf of all the authors, I declare that no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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