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Effect of Short-Term Zero Tillage and Legume Intercrops on Soil Quality, Agronomic and Physiological Aspects of Cotton under Arid Climate

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Abstract: A detailed field experiment was carried out to study the effect of conventional and zero tillage and legume intercrops on soil health indicators and cotton productivity and also yield components of leguminous crops at the Research Farm, MNS-University of Agriculture, Multan, Pakistan. The field experiment was comprised of four legume intercrops (no intercrops (sole cotton), mung bean, mash bean, and soybean) and two tillage systems (three years zero tillage (ZT) and long-term conventional tillage (CT)). The CT showed the highest plant height (121 cm), total bolls per plant (22.9 bolls), boll weight (2.74 g) and seed yield (2031 kg ha^{-1}) of the cotton crop, as compared to ZT. The highest leaf transpiration rate (9.28 mmol H_2O m^{-2} s^{-1}), net leaf photosynthetic rate (27.17 µmol m^{-2} s^{-1}), stomatal conductance (0.493 mmol m^{-2} s^{-1}), chlorophyll content (62.3 SPAD value), plant height (123 cm), total bolls per plant (24.4), boll weight (2.83 g), and seed yield (2090 kg ha^{-1}) of cotton crop were recorded when it was grown as a sole crop, as compared to legume intercrops. However, soil organic matter (0.77%), phosphorus (8.08 mg kg^{-1}), potassium (253 mg kg^{-1}), and microbial population (7.26 $\times$ 10^6 Cfu) were higher in ZT than in CT. Mung bean showed a maximum number of pods (32), seed yield (173 kg ha^{-1}), biomass (950 kg ha^{-1}), and harvest index (19.0%), when intercropped with cotton. The highest land equivalent ratio and area time equivalent ratio were recorded in mung bean and cotton intercropping, grown under a CT system. Furthermore, the maximum benefit-cost ratio was recorded in mung bean and cotton intercropping, over sole cotton cropping under CT (1.75) and ZT (1.67) systems. The ZT and intercropping of leguminous crops with cotton might be a promising option for increasing the seed cotton yield, seed yield of leguminous crops, system profitability, and sustainability of soil health.

Keywords: legume intercrop; soil productivity; sustainable agriculture; tillage practices; soil organic matter (SOM)

1. Introduction

Cotton (*Gossypium hirsutum* L.) is known as white gold and is extensively cultivated all over the world. It is a major fiber crop, with an economic impact of more than USD 600 billion per year, worldwide [1]. It is the primary driver of the textile industry [2]. Pakistan positioned fourth among cotton-producing countries, after India, China, and the USA, and is the seventh largest cloth producer, globally [3]. Its production remained at 11.94 million bales, from 2699 thousand hectares, having a share of 1% in the gross domestic product (GDP) and 5.50% in agriculture value addition [3]. However, cotton productivity is affected by low seed quality, water shortage, high input price, soil fertility depletion [4]. The agronomic factors, including tillage operations, improper irrigation, and sowing techniques, significantly further decrease cotton yield and production [5,6]. Notably, the adoption of intensive tillage and mono-cropping of cotton leads to a depletion of soil health and its productivity [7]. Excessive monoculture and conventional tillage practices cause soil erosion, degradation of soil structure, increased nutrient depletion, and reduced water retention capacity [8].

Nevertheless, many countries could undergo issues related to low soil fertility and poor soil quality, due to land use changes, soil erosion, deforestation, and extreme climatic conditions in the future, especially arid and semi-arid regions in the Middle East, Asia, and Australia [9,10]. The aim, now, should be focused on sustainable land development strategies that facilitate the fulfillment of needs of the current population, without compromising the resources, and preserving the resources to meet the demand of future generations [11]. Indeed, sustainable agriculture is part of a sustainable land development strategy that emphasizes the long-term production of food and cash crops, with minimal environmental effects and improved soil health [12]. Sustainable agriculture uses techniques that have no or minimal impacts, especially soil environments, such as soil flora and fauna [13]. These techniques include soil microbiota management [14], zero tillage [15], prevention from soil erosion [16], fallowing the soils, and cover cropping, as well as inter-cropping [17,18].

The long-term zero tillage system is a sustainable tool which can sustain soil quality and ultimately crop productivity [19]. Minimum tillage and zero tillage practices improve the availability of soil phosphorus, potassium, soil organic matter under arid climatic conditions [19,20]. Similarly, many field trials have shown that soil organic matter increases under long-term zero tillage systems [21,22]. Additionally, the microbial population also showed an increasing trend under long-term zero tillage systems [23,24]. The green manure of mustard also increased soil organic matter under an arid climate [25]. Secondly, inclusion of legume intercrops increases the nitrogen budget of soil, which is attributed to its vital, in increasing the activities of microbes and nitrogen fixation [26].

Similarly, more diversified farming systems with intercropping and cover cropping are essential for restoring soil biodiversity and fertility [27]. Particularly, the intercropping of legumes and organic amendments could improve crop yield, productivity, and soil health [28]. Leguminous crops are also proven to be effective in sustaining soil fertility by supplying atmospheric N to the soil, which is attributed to the ability of legumes to fix nitrogen through the symbiotic association, called biological nitrogen fixation (BNF) [29]. Leguminous intercropping may provide many additional benefits to soil health and quality, by reducing soil erosion, improving soil processes [30], increasing moisture retention [31], improving soil fertility [32], increasing nutrient cycling, and enhancing soil conservation [33,34]. One recent field study has shown that legume crops have the potential to improve the physical properties of soil, which was attributed to its role as soil conditioner [35]. They positively affect soil physical properties, mainly due to the enormous biomass production capacity, which provides the substrate for soil biological activity that facilitates increasing soil organic matter [36].

Considering the potential benefits of zero tillage and cover crops, in the form of legumes that have not been explored, to improve cotton productivity and soil health in Pakistan, we hypothesized that zero tillage and legume intercropping might improve cotton productivity and soil health. We set the following two main objectives in this study: (i) to evaluate the effect of conventional and zero tillage and inclusion of leguminous crops on soil health indicators, cotton productivity, and yield components of leguminous crops; (ii) to identify the most suitable leguminous crop for intercropping with a cotton crop under an arid climate.

2. Materials and Methods

2.1. Site Characteristics and Climatic Conditions

The current field experiment was conducted at Research Station of MNS-University of Agriculture, Multan (30°1575 N, 71°5249 E) South Punjab, Pakistan, during summer 2019. The elevation of the experimental site was about 178 m above sea level. The experimental site was located in plain area of an arid climate under irrigated conditions. Meteorological data throughout the experimental period were recorded from an automatic weather station of MNS-University of Agriculture, Multan, Pakistan, installed 400 m away from the experimental site. During the experimental period, the recorded mean maximum and minimum temperatures were 39.9 °C in June and 15.1 °C in October, respectively (Figure 1). Before the field experimentation, the soil samples were collected to depths of 0–15 cm from each corresponding experimental unit and analyzed accurately to determine the different physicochemical properties of the soil profile. The experimental soil was clay (clay (49%), silt (32%), and sand (19%)) having soil pH (8.03), electrical conductivity (3.44 dS m^{-1}), soil organic matter (0.73%), phosphorus (7.58 mg kg^{-1}), potassium (236 mg kg^{-1}), and microbial population (6.68 × 10^6 CFU (Colony-forming Unit)).

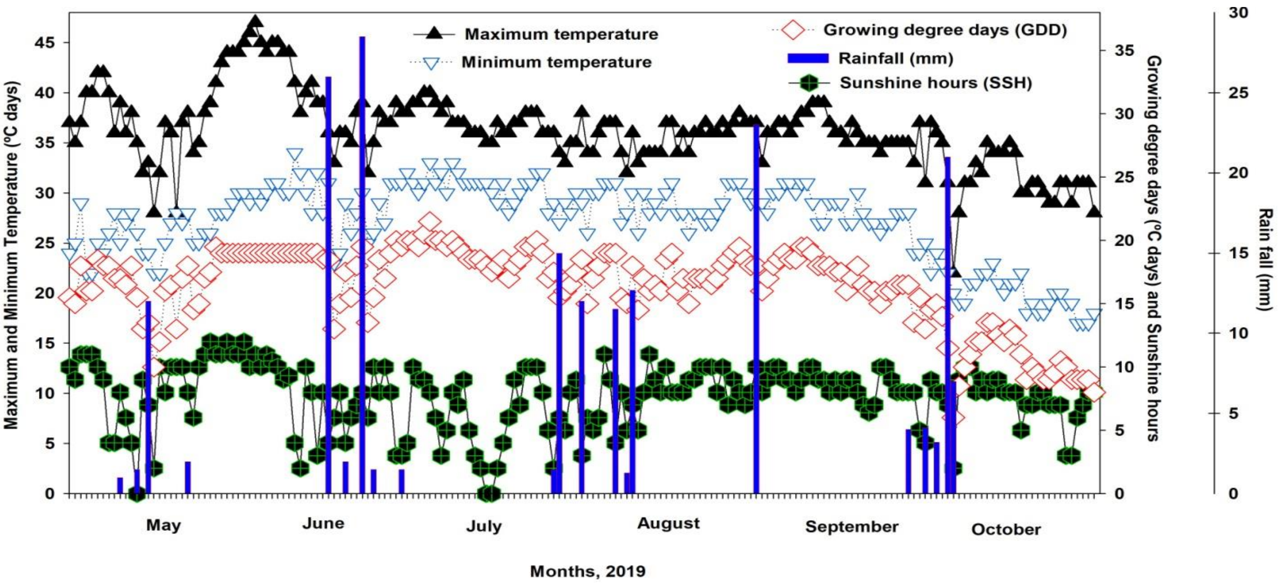

Figure 1. Data of daily weather variables (maximum and minimum temperature, sunshine hours, growing degree days (cotton), and rainfall) during crop growing season in 2019.

2.2. Experimental Details

The field experiment was laid out in a split-plot under randomized complete block design (RCBD) with four replications. The experiment comprised of two tillage systems and four legume intercrop patterns with four replications (32 experimental units); CT = conventional tillage, wheat residues incorporated, ZT = zero tillage, wheat residues retained; C_1 = cotton + soybean (1:1), C_2 = cotton + mash bean (1:1), C_3 = cotton + mung bean (1:1), and C_4 = sole cotton. The CT and ZT were considered main plots in the design, whereas C1, C2, C3 and C4 were subplots. The plot size was 84 m^2 (14 m × 6 m) and each plot was separated from the other by a distance of 0.5 m.

Prior to the current field experiment, zero-till plots were not tilled (no-till wheat crop, seedling sowing by direct drilling) in last two years which indicates zero-till plots related to third years zero-till (no-till); initial soil properties were related to the first year under no-till. The CT plots from long-term experiment were used for CT in current experiment. In the CT system, experimental plots were prepared using traditional disc plough to the depth of 30 cm, followed by proper planking to incorporate the wheat crop residues into the soil. However, ZT meant there was sowing of cotton seeds after wheat harvesting directly on the untilled soil which retained 50% wheat crop residues. Weeds were removed manually without disturbing the wheat crop residues in the ZT system. Cotton variety BS-15 was sown on 10 May 2019, with seed rate of 15 kg ha^{-1} in both tillage systems using a tractor-mounted Kharif drill. Furthermore, after 30 days of sowing (at first irrigation), cover crops (mung bean variety NM-2016, mash bean variety Urooj, and soybean variety Faisal soybean) were intercropped with cotton crop. One-third of the dose of nitrogen (of total 160 kg ha^{-1}) and recommended doses of P (90 kg ha^{-1}) and K (60 kg ha^{-1}) were applied at the time of sowing as basal application. The remaining N was divided into three equal splits of 35.6 kg ha^{-1} and used at 1st, 3rd and 5th irrigation. Good quality irrigation was achieved from the canal irrigation system by a diesel-operated water-lifting pump at prescribed irrigation scheduled stages (1st irrigation was done at 30 days after sowing and subsequent irrigations at 10–15 day intervals depending upon weather conditions and crop requirements).

2.3. Measurements and Analytical Procedures

2.3.1. Phenological, Physiological, and Yield Attributes of the Cotton Crop

The number of days required for 1st square formation, 1st flower formation, 1st boll opening, and 1st boll maturity was recorded in each plot for cotton. A total of five plants were selected and tagged randomly from each experimental unit. At the full canopy development stage, the observations, including stomatal conductance, net leaf photosynthesis rate, and net leaf transpiration rate were recorded with the help of the CIRAS-3 Portable Photosynthesis System. Similarly, chlorophyll content was estimated using a chlorophyll meter (SPAD-502; Minolta, Tokyo, Japan). Agronomic traits including plant height (from base to the tip of the main stem), mature and effective bolls per plant (before the start of picking), and mean boll weight (ten bolls were randomly chosen from each experimental unit) were calculated. The seed cotton yield obtained from the net plot area was added into the seed cotton weight of the previously picked ten bolls and was converted as seed cotton yield (kg ha^{-1}).

2.3.2. Number of Pods Per Plant, Seed Yield, Biomass, and Harvest Index of Leguminous Intercrops

In each experimental unit, the number of pods of five randomly tagged plants of mung bean, mash bean, and soybean were counted, and the mean number of pods per plant was calculated. The mung bean, mash bean, and soybean were harvested from each experimental unit and sun-dried. After sun-drying, harvested plants of mung bean, mash bean, and soybean were threshed, and the seed yield of each experimental unit was calculated and converted into seed yield (kg ha^{-1}) by using the below formula.

$$\text{Seed yield (kg/ha)} = \frac{\text{Seed yield (kg/plot)} \times 10,000\ \left(\text{m}^2\right)}{\text{Net plot area}\ \left(\text{m}^2\right)} \quad (1)$$

At maturity, the plants were harvested from an area of 1 m^2 to compute the biomass. The harvested samples were sun-dried until samples showed a constant weight. Then the recorded dry weight of samples was converted into biomass (kg ha^{-1}). Moreover, the harvest index was calculated by using the formula given below.

$$\text{Harvest index (\%)} = \frac{\text{Seed yield (kg/ha)}}{\text{Biological yield(kg/ha)}} \quad (2)$$

2.3.3. Determination of Soil Physicochemical Properties

According to experimental treatments, five soil samples (0–30 cm depth) were collected using a soil auger from each experimental unit after harvesting and analyzed for the different physio-chemical properties of soil. Saturated soil paste was prepared; soil pH and electrical conductivity were measured using a pH meter and electrical conductivity meter, respectively. Then, the soil samples were dried and sieved (2-mm mesh). Soil organic matter was analyzed using the wet oxidation method [37]. Soil available N, P, and K were estimated by using the protocols of alkaline potassium permanganate [38], sodium bicarbonate [39], and ammonium acetate [40], respectively. Furthermore, the soil microbial population was assessed using Starkey's medium in a colony-forming unit (CFU) using the equation below.

$$\text{CFU per ml of Sample} = \frac{\text{Number of colonies}}{\text{Amount planted } \times \text{Dilution}} \quad (3)$$

2.3.4. Statistical Analysis

Analysis of variance (ANOVA) for all the study parameters was used for the statistical analysis. Further, Tukey's honestly significant difference (HSD) test for mean comparison was used to distinguish differences between treatment means at $p \leq 0.05$ as a significant level [41].

2.3.5. Economic Analysis and Assessment of System Productivity

The economic analysis was done by using the standard protocols and procedures of CIMMYT (1988). Land equivalent ratio (LER) and area time equivalent ratio (ATER) were assessed for all treatments.

3. Results

3.1. Phenological Attributes

The effects of tillage systems on phenological traits, including the number of days to first square formation, first flower formation, first boll opening, and first boll maturity, are presented in Table 1. However, the effects of legume intercrops were significant for the days to first square and flower formation but were not significant for days to first boll opening and boll maturity (shown in Figure 2). The interaction of the tillage system and legume intercrops had no significant effect on these traits. However, the trend was observed differently in terms of the main effect of tillage systems and leguminous intercropping on them (Table 1). The cotton crop grown under CT, with wheat residue incorporated, took more time for the number of days to first square formation (36.9), first flower formation (61.6), first boll opening (90.0), and first boll maturity (104.5), compared to ZT with wheat residue retained (Table 1). Furthermore, the treatment C_4 (sole cotton crop) took fewer days to achieve the number of days to first square formation (36.3) and first flower formation (59.0) of the cotton crop, as compared to C_3, C_2 and C_1; the treatments C_1, C_2, and C_3 were statistically on par for these two traits, but significantly differed from C_4 ($p \leq 0.05$), shown in Figure 2. All treatments in leguminous intercropping recorded the same number of days to first boll opening, and first boll maturity; they did not demonstrate a statistically significant difference for this trait (Figure 2).

Table 1. Effect of different tillage systems on phenological, physiological, morphological, and yield-related attributes of cotton crop, and soil health indicators.

Treatments	DSF	DFF	DBO	DBM
Tillage Systems (TS)				
CT	36.9 a	61.6 a	90.0 a	104.5 a
ZT	38.4 b	62.4 b	92.6 b	102.0 b
HSD ($p \leq 0.05$)	1.10	0.50	0.50	0.596
Tillage Systems (TS)	NLTR	NLPR	SC	CHC
CT	8.70	241	0.466	56.8
ZT	8.40	236	0.464	58.2
HSD ($p \leq 0.05$)	NS	NS	NS	NS
Tillage Systems (TS)	PH	TBPP	MBW	SCY
CT	121 a	22.9 a	2.74 a	2031 a
ZT	116 b	21.4 b	2.37 b	1889 b
HSD ($p \leq 0.05$)	4.00	0.30	0.21	80.0
Tillage Systems (TS)	SOM	P	K	MP
CT	0.75 b	7.84 b	245 b	7.04 b
ZT	0.77 a	8.08 a	253 a	7.26 a
HSD ($p \leq 0.05$)	0.02	0.055	1.866	0.062

Mean sharing of the same case letter did not significantly differ at $p \leq 0.05$; DSF = days to first square formation; DFF = days to first flower formation; DBO = days to first boll opening; DBM = days to first boll maturity; NLTR = net leaf transpiration rate (mmol H_2O m^{-2} s^{-1}); NLPR = net leaf photosynthesis rate (μmol m^{-2} s^{-1}); SC = stomatal conductance (mmol m^{-2} s^{-1}); CHC = chlorophyll content (SPAD value); PH = plant height (cm); TBPP = total bolls per plant; MBW = mean boll weight; SCY = seed cotton yield (kg ha^{-1}); SOM = soil organic matter (%); P = soil available phosphorus (mg kg^{-1}); K = soil available phosphorus (mg kg^{-1}); MP = soil microbial population (10^6 CFU).

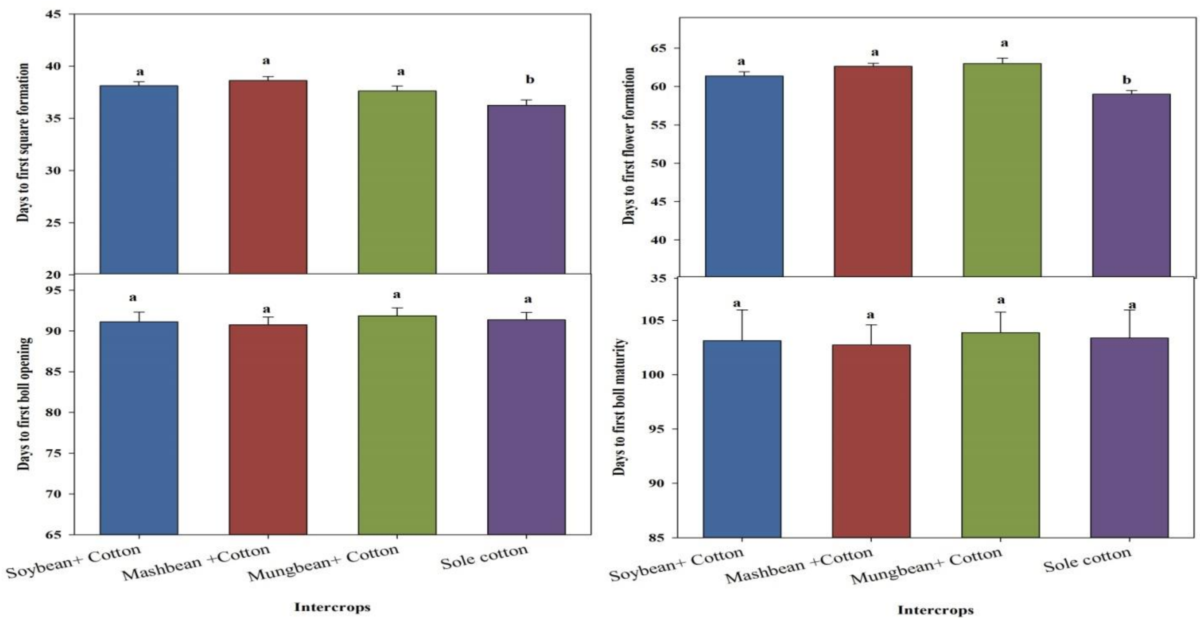

Figure 2. Effect of different legume intercrops on phenological attributes of the cotton crop under arid climatic conditions (tillage systems data are presented in Table 1, as some parameters were not significant, making them difficult to present in graph form). (Letter "a" on all graph bars showed the non-significance of the data at $p \leq 0.05$.

3.2. Physiological Attributes

The results for physiological attributes, such as leaf transpiration rate, leaf photosynthetic rate, stomatal conductance, and SPAD value, are presented in Table 1 and Figure 3. The treatments C_1, C_2, C_3 and C_4 differed significantly for the leaf photosynthesis rate, stomatal conductance, and chlorophyll content of the cotton crop ($p \leq 0.05$), which is shown in Figure 3. The sole cotton, C_4, showed the highest leaf transpiration rate (9.28 mmol H_2O m^{-2} s^{-1}), net leaf photosynthetic rate (27.17 µm m^{-2} s^{-1}), stomatal conductance (0.493 mmol m^{-2} s^{-1}), and chlorophyll content (62.3 SPAD value). However, different tillage systems, CT and ZT, did not significantly affect the leaf transpiration rate, leaf photosynthetic rate, stomatal conductance, or chlorophyll content (Table 1). Similarly, the interaction of tillage systems and legume intercrops had no significant effect on these traits. Stomatal conductance, chlorophyll content, net leaf photosynthetic, and net leaf transpiration rate of the cotton crop showed a significant positive Pearson correlation with each other (Figure 3).

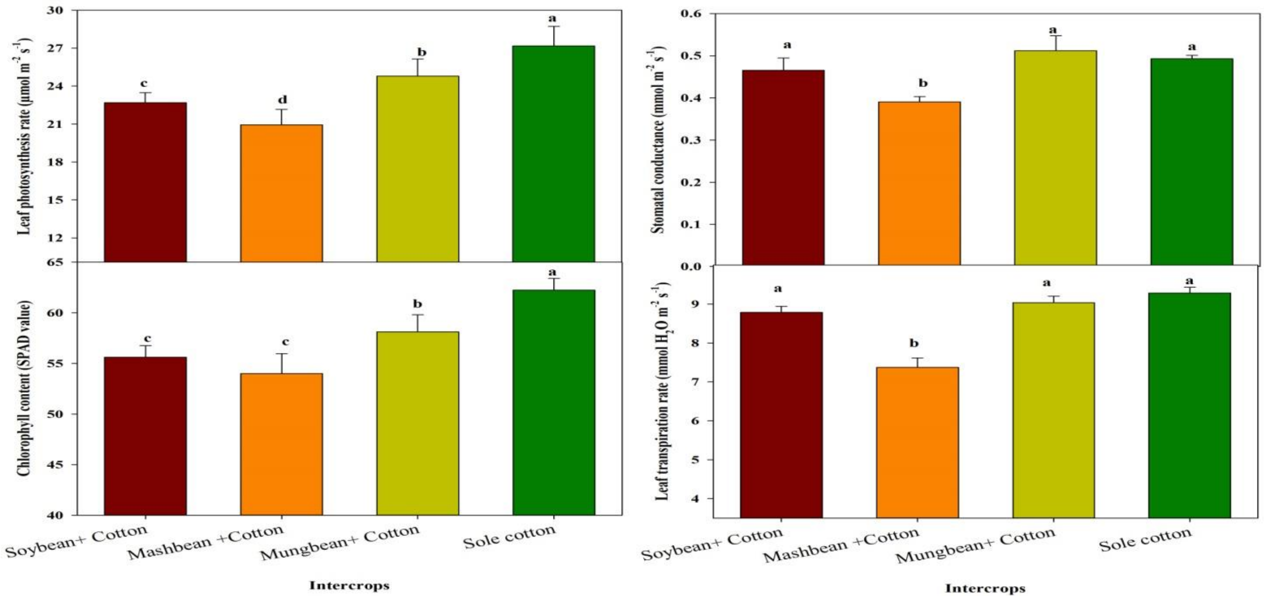

Figure 3. Effect of different legume intercrops on physiological attributes of the cotton crop under arid climatic conditions (tillage systems did not significantly affect the physiological attributes of the cotton crop at ≤ 0.05, hence, data are presented in Table 1). (Letters on graph bars "a–d" showed significant differences at $p \leq 0.05$).

3.3. Yield and Yield-Related Attributes of the Cotton Crop

Plant height, total bolls per plant, mean boll weight, and seed cotton yield in cotton were influenced by the main effects of tillage systems and legume intercrops (Table 1 and Figure 4). The cotton crop grown under CT showed higher plant height (121 cm), total bolls per plant (22.9 bolls), mean boll weight (2.74 g), and seed cotton yield (2031 kg ha^{-1}) compared to ZT (Table 1). Moreover, C_4 (sole cotton) showed the highest plant height (123 cm), which was statistically on par with C_3 (cotton and mung bean) and C_1 (cotton and soybean) intercropping systems. Likewise, C_4 (sole cotton) showed the highest mean boll weight (2.83 g) which was on par with the C_3 (cotton and mung bean) intercropping system (Figure 4). A similar trend was observed for total bolls per $plant^{-1}$ (24.4 bolls), and seed cotton yield (2090 kg ha^{-1}), as shown in Figure 4. Nevertheless, the interaction between tillage systems, with the intercropping of leguminous crops, did not affect the plant height, total bolls per $plant^{-1}$, mean boll weight, and cotton seed yield. Furthermore, plant height, total bolls per plant, mean boll weight, and seed cotton yield of the cotton crop also showed a significant positive Pearson correlation with each other (Figure 4).

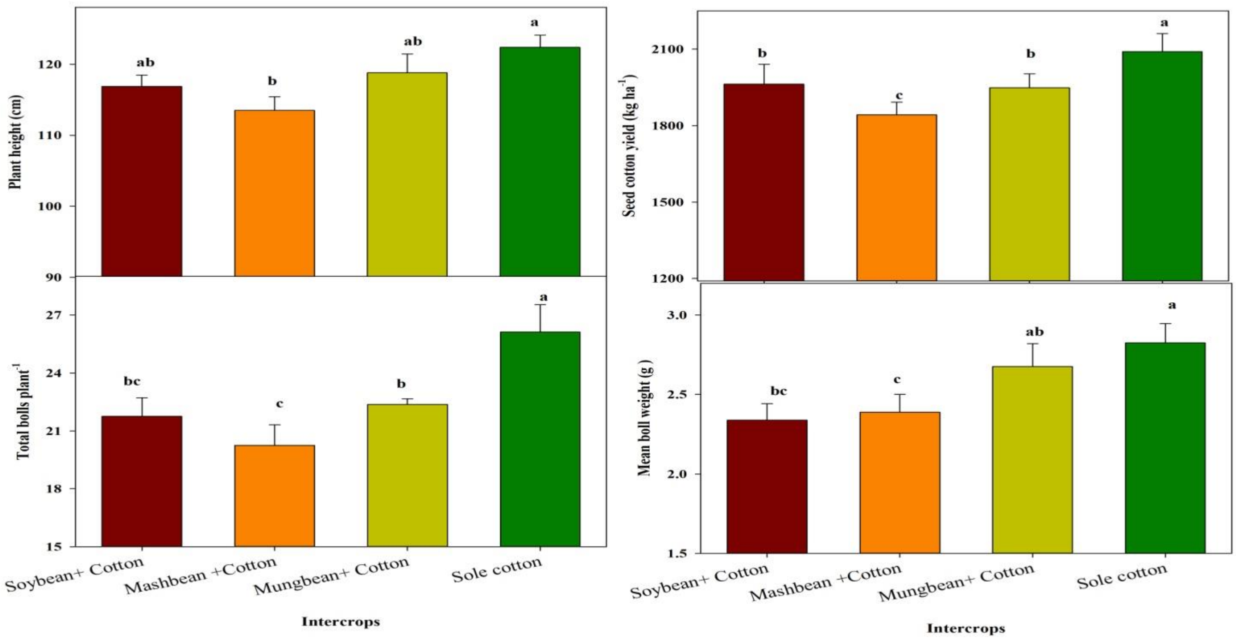

Figure 4. Effect of different legume intercrops on morphological and yield attributes of the cotton crop under arid climatic conditions. (Letters on graph bars "a, b, c, ab, and bc" showed significant differences at $p \leq 0.05$). (Tillage systems data are presented in Table 1, as some parameters were not significant, making them difficult to present in graph form.).

3.4. Yield and Yield-Related Attributes of Leguminous Intercrops

The results, including pods per plant, seed yield, biological yield, and harvest index of legume intercrops, are presented in Table 2 They were affected significantly by the main effect due to tillage systems and legume intercrops, except for biological yield in the case of different tillage systems. The highest pods per plant (31), seed yield (163 kg ha^{-1}), biological yield (907 kg ha^{-1}), and harvest index (18%) were observed in CT, as compared to ZT. However, the interaction of tillage systems with the intercropping of legume intercrops was observed as non-significant for these traits. Among leguminous intercrops, mung bean intercropped with cotton (C_3) had the highest pods per plant, seed yield, biological yield, and harvest index (Table 2).

Table 2. Effect of different tillage systems and legume intercrops on pods per plant, seed yield, biological yield, and harvest index of leguminous intercrops.

Treatments	Pods Per Plant	Seed Yield (kg ha^{-1})	Biological Yield (kg ha^{-1})	Harvest Index (%)
Tillage Systems (TS)				
CT	31.0 a	163 a	907	18.0 a
ZT	28.0 b	124 b	867	15.0 b
HSD ($p \leq 0.05$)	0.90	4.10	NS	0.90
Leguminous intercrops (LI)				
C_1	31.0 a	118 c	866 b	14.0 b
C_2	26.0 b	139 b	841 b	16.0 b
C_3	32.0 a	173 a	950 a	19.0 a
HSD ($p \leq 0.05$)	2.20	23.70	79	2.00
TS	NS	**	NS	**
LI	*	**	**	**
TS × LI	NS	NS	NS	NS

CT = Conventional tillage; ZT = Zero tillage; C_1 = Cotton + Soybean (1:1); C_2 = Cotton + Mash bean (1:1); C_3 = Cotton + Mung bean (1:1); C_4 = Sole cotton; Means sharing same case letter for parameters did not differ significantly at $p \leq 0.05$; * = Significant at $p \leq 0.05$; ** = Significant at $p \leq 0.01$; NS = Non-significant at $p \leq 0.05$.

3.5. Soil Health Indicators

The results about soil health indicators, i.e., soil organic matter (SOM), microbial population (MP), soil available P and K, are presented in Table 1 and Figure 5. They were influenced significantly by different tillage systems and legume intercrops. ZT showed improvement in SOM (0.77%), MP (7.26 × 10^6 CFU), soil available P (8.08 mg kg^{-1}) and K (253 mg kg^{-1}) and all were recorded under ZT. Similarly, the inclusion of legume intercrops improved SOM, MP, soil available P and K. The highest SOM (0.75%), MP (7.32 × 10^6 CFU), soil available P (8.12 mg kg^{-1}), and K (251 mg kg^{-1}) were recorded in the intercropping systems, C_1, C_2 and C_3 (Figure 5). Nonetheless, the interaction of tillage systems with legume intercrops was non-significant for soil health indicators. Moreover, soil organic matter, soil available phosphorus and potassium, and microbial population showed a significant negative Pearson correlation with each other (Figure 6). The number of pods per plant, seed yield, biological yield, and harvest index of leguminous crops also showed a significant positive Pearson correlation with each other (Figure 6).

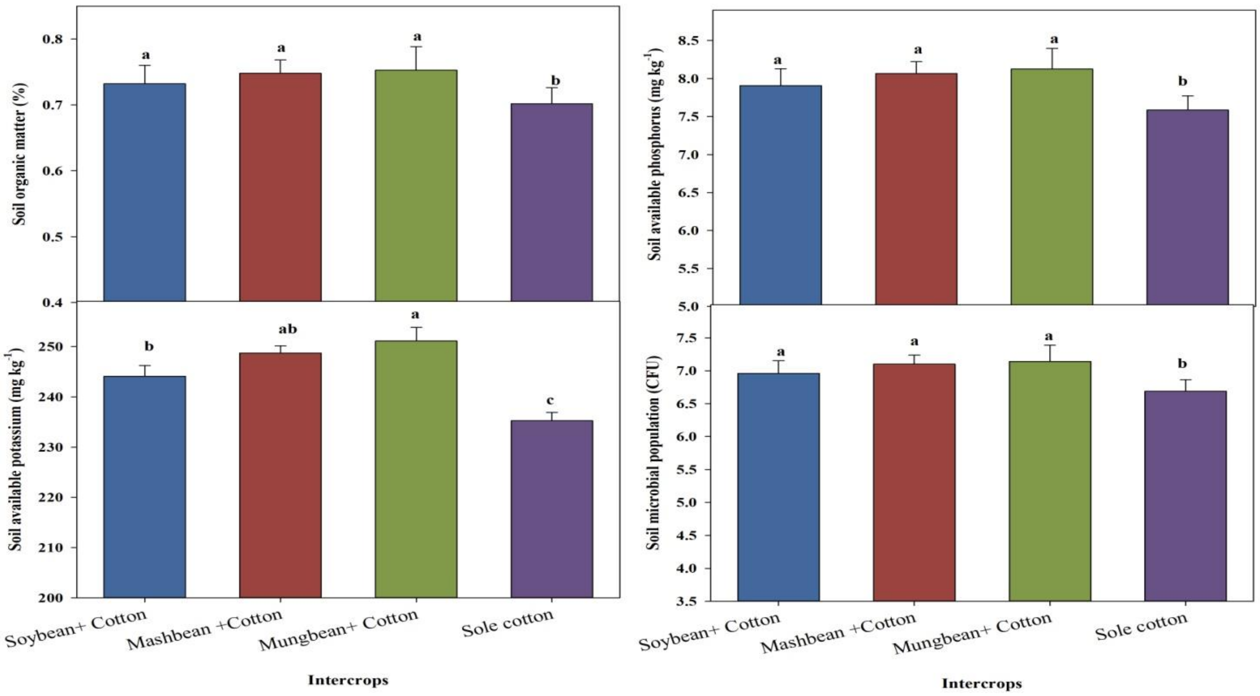

Figure 5. Effect of different legume intercrops on soil health indicators under arid climatic conditions. (Letters on graph bars "a, b, c, and ab" showed significant differences at $p \leq 0.05$). (Tillage systems data are presented in Table 1, as some parameters were not significant, making them difficult to present in graph form).

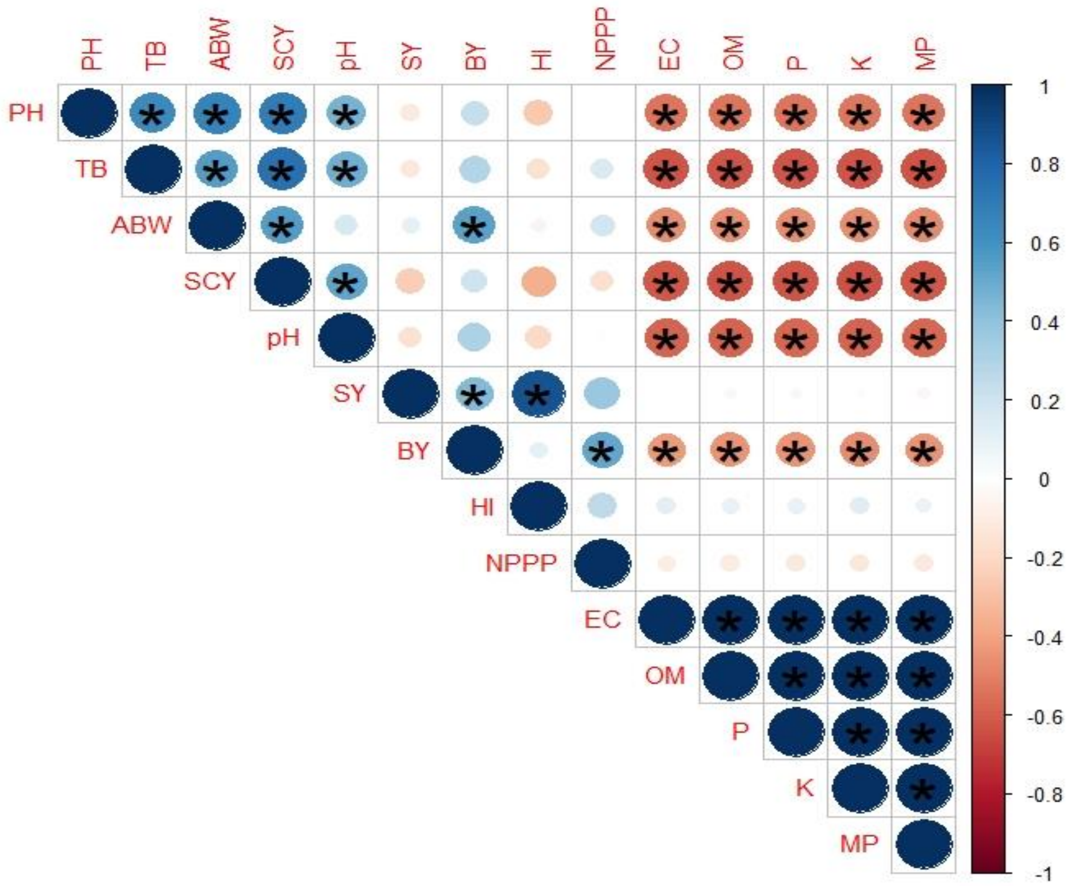

Figure 6. Correlation of growth, yield and physiological attributes of cotton crop, yield components of legume intercrops and soil health indicators under different tillage systems and legume intercrops; the areas of circles show the absolute value of corresponding correlation coefficients tested at * 0.01 significant level. PH = Plant height; TB = Total bolls per plant; ABW = Average boll weight; SCY = Seed cotton yield; BY = Biological yield; HI = Harvest index; NPPP = Number of pods per plant; EC = Electrical conductivity; OM = Organic matter; P = Soil available phosphorus; K = Soil available potassium; MP = Microbial population; pH = soil pH; SY= seed yield.

3.6. System Productivity

In the current study, the land equivalent ratio (LER) and area time equivalent ratio (ATER) were recorded as the maximum in mung bean and cotton intercropping, grown under CT (conventional tillage system) (Table 3). The effect of different tillage systems and legume intercrops on system productivity is summarized in Table 4. The positive aggressivity value of the cotton crop, in both conventional and zero tillage, indicated that cotton was dominant over legumes. The level of aggressivity was higher in soybean and cotton intercropping and decreased in mash bean and cotton and mung bean and cotton intercropping. The maximum benefit-cost ratio was recorded in mung bean and cotton intercropping, under CT and ZT systems (Table 5).

Table 3. Effect of different tillage systems and legume intercrops on land equivalent ratio and area time equivalent ratio of system productivity.

Treatments	Legumes Intercropping (LI)		
	Land Equivalent Ratio		
Tillage Systems	C_1	C_2	C_3
CT	1.06	1.04	1.11
ZT	1.04	0.99	1.06
	Area Time Equivalent Ratio		
Tillage Systems	C_1	C_2	C_3
CT	1.03	1.00	1.07
ZT	1.01	0.96	1.03

Table 4. Effect of different tillage systems and legume intercrops on the aggressivity of system productivity.

Treatments		Aggressivity	
ZT	Cotton		Intercrop
		Conventional tillage	
	C_1	0.84	−0.84
	C_2	0.76	−0.76
	C_3	0.79	−0.79
CT		Zero tillage	
	C_1	0.80	−0.80
	C_2	0.75	−0.75
	C_3	0.74	−0.74

CT = Conventional tillage; ZT = Zero tillage; C_1 = Cotton + Soybean (1:1); C_2 = Cotton + Mash bean (1:1); C_3 = Cotton + Mung bean (1:1); C_4 = Sole cotton.

Table 5. Effect of different tillage systems and legume intercrops on the economics of the system.

Treatment	Variable Cost	Fixed Cost	Total Cost	Gross Income	Net Benefits	BCR
CTC_1	5430	110,000	115,430	194,982	79,552	1.67
CTC_2	7274	110,000	117,274	190,485	73,211	1.65
CTC_3	4980	110,000	114,980	202,030	87,050	1.75
CTC_4	3500	110,000	112,000	192,240	80,240	1.71
ZTC_1	3430	110,000	113,430	172,575	59,145	1.47
ZTC_2	3274	110,000	115,274	178,740	63,466	1.54
ZTC_3	2980	110,000	112,980	181,480	68,500	1.67
ZTC_4	1120	110,000	111,120	183,870	72,750	1.57

CT = Conventional tillage; ZT = Zero tillage; C_1 = Cotton + Soybean (1:1); C_2 = Cotton + Mash bean (1:1); C_3 = Cotton + Mung bean (1:1); C_4 = Sole cotton.

4. Discussion

The cotton crop grown under ZT took less time for the completion of different phenological stages, such as days to first square formation, first flower formation, first boll opening, and first boll maturity (Table 1). It is similar to the previous study in cotton, under a zero-tillage system [42]. Moreover, the sole cotton crop, C_4, took less time for all the above-mentioned phenological traits (Figure 2) and better physiological attributes (net leaf photosynthetic rate, net leaf transpiration rate, stomatal conductance, and chlorophyll content) were recorded due to suitable soil and other environmental conditions (Figure 2). This is because there is no competition for light, space, water, and nutrient acquisition, leading to high growth and development, leading to improved phenological attributes [43]. The CT system showed higher values for the physiological traits of the cotton crop, measured in previous research, than the ZT system (Table 1). It might be due to the maximum root growth and development, which ultimately accounted for increased assimilate partitioning and high physiological attributes [44]. However, the current results did not show significant differences under CT and ZT.

CT significantly improved the morphological, yield and yield-related attributes of the cotton crop, having higher plant height, total bolls per plant, mean boll weight, and seed cotton yield, compared to ZT (Table 1), which might be due to higher root penetration into the soil and higher nutrients uptake (N, P, and K), to meet the growth requirements of the cotton crop [45]. Several studies have reported that the morphological and yield attributes of the cotton crop improve under a conventional tillage system in the initial years [46]. However, the seed cotton yield increased under ZT, due to better soil porosity [42] and improved water use efficiency [47,48]. In our findings, legume intercrops improved the plant height, total bolls per plant, and mean boll weight, which could be associated with the increased nitrogen availability due to nitrogen fixation of the legume crops [31,33].

In the current study, legume intercrops, grown under a CT system, accelerated the number of pods per plant, seed yield, biological yield, and harvest index compared to ZT. It is also evident that a previous study had reported the same results under CT [49]. It might be because of the effective use of nitrogen under optimal seedbed for ideal growth and development that the yield of leguminous crops ultimately improved [31,50]. Several other studies have also concluded that CT enhances the yield of legume intercrops [50]. Current findings of the experiment showed that, mung bean intercropped with cotton (C_3) set the highest values for the yield and yield-related attributes, which might be due to higher nitrogen fixation and optimum growth conditions for mung beans [51].

Conservation tillage (zero tillage) is a promising option, which maintains soil health indicators under an arid climate [19]. It increases the available soil phosphorus, potassium, organic matter, and ultimately soil health indicators [20,21]. Furthermore, due to improved soil quality indicators, SOM, available soil phosphorus, and potassium were higher under ZT. Similarly, legume intercrop mung beans showed higher soil quality indicators (SOM, P, K). Earlier studies found similar results for higher soil organic matter under ZT and leguminous intercropping [22,23]. Finally, the soil microbial population was recorded as higher under ZT, as compared to CT, which might be due to improved soil quality indicators under ZT [26,28]. These results align with Rajpoot et al. [52] where soil microbial population and activities were enhanced under zero tillage. A higher microbial population recorded in leguminous intercropping might be attributed to the greater biomass of legume intercrops [53,54].

In our results, the maximum land equivalent ratio (LER) and area time equivalent ratio (ATER) were recorded in mung bean and cotton intercropping, grown under a CT. Dhima et al. [55] stated similar findings, that the LER and ATER of intercropped legumes were more than for sole crop, which highlighted an advantage of intercropping over the mono-cropping pattern, in using environmental resources for plant growth. Cotton dominated all of the intercropped legumes. The low aggressivity of mash bean and cotton intercropping in a CT system and mung bean and cotton intercropping in a zero tillage system proves that mash beans and mung beans are less competitive to cotton in CT and ZT systems, respectively. In current study the higher aggressivity value of soybean and cotton intercropping suggests that soybeans are the most competitive legume crop to cotton. The maximum benefit-cost ratio was recorded in mung bean and cotton intercropping, under both CT and ZT systems, suggesting that this is the best intercropping system for cotton farmers. The higher seed cotton yield and mung bean yield increased the net benefits and, ultimately, economic benefit ratio. The results and findings showed the significance of the issues, as similar aspects have been investigated in previous studies, under arid to semi-arid climatic conditions [56–61].

5. Conclusions

The current study indicated that conventional tillage and leguminous crop intercropping performed better in terms of phenological, physiological, morphological, and yield attributes. However, soil analysis results revealed that zero tillage and leguminous crop intercropping somewhat improved soil health indicators. Moreover, the leguminous crop "mung bean" showed the maximum number of pods, seed yield, biological yield, and harvest index, when intercropped with the cotton crop. Furthermore, the maximum benefit-cost ratio was recorded from mung bean and cotton intercropping under conventional tillage. In conclusion, zero tillage and the intercropping of leguminous crops with cotton crops could be recommended for achieving higher seed cotton yield, seed yield of leguminous crops, system profitability and soil health indicators. Further research and field research trials (for farmers, extension workers, and other associated stakeholders' fields) need to be conducted to create awareness on zero tillage, the role of leguminous crops in nitrogen fixation, economic profitability, and sustaining soil health, besides improving cotton productivity. Seasonal and locational trials may also be required in the future to confirm the findings, while modeling studies may also require investigation of the effects of seasonal and climate change effects, in the longer term, on soil health and crop yield.

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References

1. Shuli, F.; Jarwar, A.H.; Wang, X.; Wang, L.; Ma, Q. Overview of the Cotton in Pakistan and its Future Prospects. *Pak. J. Agric. Res.* **2018**, *31*, 396–407. [CrossRef]
2. Ibrahim, N.A.; Moneim, N.M.A.; Halim, E.A.; Hosni, M.M. Pollution Prevention of Cotton-Cone Reactive Dyeing. *J. Clean. Prod.* **2008**, *16*, 1321–1326. [CrossRef]
3. Government of Pakistan (GOP). Agriculture. In *Economic Survey of Pakistan*; Economic Advisory Wing, Ministry of Finance, Division: Islamabad, Pakistan, 2018; pp. 14–32.
4. Abdullaev, I.; Hassan, M.U.; Jumaboev, K. Water Saving and Economic Impacts of Land Leveling: The Case Study of Cotton Production in Tajikistan. *Irrig. Drain. Syst.* **2007**, *21*, 251–263. [CrossRef]
5. Khalid, M.Z.; Ahmed, S.; Al-Ashkar, I.; EL Sabagh, A.; Liu, L.; Zhong, G. Evaluation of Resistance Development in Bemisia Tabaci Genn. (*Homoptera: Aleyrodidae*) in Cotton against Different Insecticides. *Insects* **2021**, *12*, 996. [CrossRef] [PubMed]
6. Farooq, O.; Mubeen, K.; Khan, A.A.; Ahmad, S. Sowing Methods for Cotton Production. In *Cotton Production and Uses*; Springer: Singapore, 2020; pp. 45–57.
7. Das, A.; Yadav, G.; Lal, R. *Legumes for Soil Health and Sustainable Management*; Springer: Singapore, 2018; pp. 347–484.
8. Ryken, N.; Nest, T.V.; Al-Barri, B.; Blake, W.; Taylor, A.; Bodé, S.; Ruysschaert, G.; Boeckx, P.; Verdoodt, A. Soil Erosion Rates under Different Tillage Practices in Central Belgium: New Perspectives from a Combined Approach of Rainfall Simulations and 7Be Measurements. *Soil Tillage Res.* **2018**, *179*, 29–37. [CrossRef]
9. Nosrati, K.; Collins, M.; Adrian, L. A Soil Quality Index for Evaluation of Degradation under Land Use and Soil Erosion Categories in a Small Mountainous Catchment. *Iran. J. Mt. Sci.* **2019**, *16*, 2577–2590. [CrossRef]
10. Zeraatpisheh, M.; Bakhshandeh, E.; Hosseini, M.; Alavi, S.M. Assessing the Effects of Deforestation and Intensive Agriculture on the Soil Quality through Digital Soil Mapping. *Geoderma* **2020**, *363*, 114–139. [CrossRef]
11. Broman, G.I.; Robert, K.H. A Framework for Strategic Sustainable Development. *J. Clean. Prod.* **2017**, *14*, 17–31. [CrossRef]
12. Busby, P.E.; Wagner, C.; Friesen, M.R.; Kremer, M.L.; Bennett, J.; Dangl, A. Research Priorities for Harnessing Plant Micro Biomes in Sustainable Agriculture. *PLoS Biol.* **2017**, *15*, 200–293. [CrossRef]
13. Yadav, S.K.; Soni, R.; Rajput, A.S. Role of Microbes in Organic Farming for Sustainable Agro-Ecosystem. In *Microorganisms for Green Revolution*; Springer: Singapore, 2018; pp. 241–252.

14. Jousset, A. *Application of Protists to Improve Plant Growth in Sustainable Agriculture*; Springer: Singapore, 2017; pp. 263–273.
15. Singh, R.K.; Singh, A.K.; Singh, J.B.; Singh, L. Success of Zero Tillage Technology: A Case of Knowledge Management for Sustainable Agriculture. *Ind. J. Extent. Educ.* **2016**, *12*, 110–115.
16. Bowers, C.; Toews, M.; Liu, Y.; Schmidt, J.M. Cover Crops Improve Early Season Natural Enemy Recruitment and Pest Management in Cotton Production. *Biol. Cont.* **2020**, *141*, 104149. [CrossRef]
17. Sharma, P.; Singh, A.; Kahlon, C.S.; Brar, A.S.; Grover, K.; Dia, K.; Steiner, R.L. The Role of Cover Crops towards Sustainable Soil Health and Agriculture. A Review Paper. *Am. J. Plant Sci.* **2018**, *9*, 1935–1951. [CrossRef]
18. Martin, G.; Paquette, A.; Dupras, A.; Rivest, D. The New Green Revolution: Sustainable Intensification of Agriculture by Intercropping. *Sci. Total Environ.* **2018**, *615*, 767–772. [CrossRef] [PubMed]
19. Busari, M.A.; Kukal, S.S.; Kaur, A.; Bhatt, R.; Dulazi, A.A. Conservation Tillage Impacts on Soil, Crop and the Environment. *Int. Soil Water Conserv. Res.* **2015**, *3*, 119–129. [CrossRef]
20. Bhatt, R. Zero Tillage Impacts on Soil Environment and Properties. *J. Environ. Agric. Sci.* **2017**, *10*, 1–19.
21. Sayed, A.; Sarker, A.; Kim, J.E.; Rahman, M.; Mahmud, M.G.A. Environmental Sustainability and Water Productivity on Conservation Tillage of Irrigated Maize in Red Brown Terrace Soil of Bangladesh. *J. Saudi Soc. Agric. Sci.* **2020**, *19*, 276–284. [CrossRef]
22. Duggan, L.; Yeates, J.; Stephen, A.; Greg, B. Bed Preparation Techniques and Herbicide Tolerance Technology for Tropical Dry Season Cotton Production. *Trop. Agric.* **2005**, *82*, 233–240.
23. Page, K.L.; Dang, Y.P.; Dalal, R.C. The Ability of Conservation Agriculture to Conserve Soil Organic Carbon and the Subsequent Impact on Soil Physical, Chemical, and Biological Properties and Yield. *Front. Sustain. Food Syst.* **2020**, *4*, 31. [CrossRef]
24. Saha, L.; Bauddh, K. Sustainable Agricultural Approaches for Enhanced Crop Productivity, Better Soil Health, and Improved Ecosystem Services. In *Ecological and Practical Applications for Sustainable Agriculture*; Springer: Singapore, 2020; pp. 1–23.
25. Koishi, A.; Bragazza, L.; Maltas, A.; Guillaume, T.; Sinaj, S. Long-Term Effects of Organic Amendments on Soil Organic Matter Quantity and Quality in Conventional Cropping Systems in Switzerland. *Agronomy* **2020**, *10*, 1977. [CrossRef]
26. Moran, P.J.; Greenberg, S.M. Winter Cover Crops and Vinegar for Early-Season Weed Control in Sustainable Cotton. *J. Sustain. Agric.* **2008**, *32*, 483–506. [CrossRef]
27. Brussaard, L.; Ruiter, P.C.; Brown, G.G. Soil Biodiversity for Agricultural Sustainability. *Agric. Ecosyst. Environ.* **2007**, *121*, 233–244. [CrossRef]
28. Baritz, R.; Wiese, L.; Verbeke, I.; Vargas, R. Voluntary Guidelines for Sustainable Soil Management: Global Action for Healthy Soils. In *International Yearbook of Soil Law and Policy 2017*; Springer: Cham, Switzerland, 2018; pp. 17–36.
29. Fustec, J.; Lesuffleur, F.; Mahieu, S.; Cliquet, J.B. Nitrogen Rhizodeposition of Legumes. A Review. *Agron. Sustain. Dev.* **2010**, *30*, 57–66. [CrossRef]
30. Hauggaard-Nielsen, H.; Jornsgaard, B.; Kinane, J.; Jensen, E.S. Grain Legume-Cereal Intercropping: The Practical Application of Diversity, Competition and Facilitation in Arable and Organic Cropping Systems. *Renew Agric. Food Syst.* **2007**, *23*, 3–12. [CrossRef]
31. Ghanbari, A.; Dahmardeh, M.; Siahsar, B.A.; Ramroudi, M. Effect of Maize-Cowpea (*Vignaunguiculata,* L.) Intercropping on Light Distribution, Soil Temperature and Soil Moisture in Arid Environment. *J. Food Agric. Environ.* **2010**, *8*, 102–108.
32. Hauggaard, N.H.; Gooding, M.; Ambus, P.; Corre-Hellou, G.; Crozat, Y.; Dahlmann, C.; Dibet, A.; von Fragstein, P.; Pristeri, A.; Monti, M.; et al. Pea-Barley Intercropping for Efficient Symbiotic N2–Fixation, Soil N Acquisition and Use of Other Nutrients in European Organic Cropping Systems. *Field Crop. Res.* **2009**, *113*, 64–71. [CrossRef]
33. Lithourgidis, A.S.; Dordas, C.A.; Damalas, C.A.; Vlachostergios, D.N. Annual Intercrops: An Alternative Pathway for Sustainable Agriculture. *Aust. J. Crop. Sci.* **2011**, *5*, 396–410.
34. Chalka, M.K.; Nepalia, V. Nutrient Uptake Appraisal of Maize Intercropped with Legumes and Associated Weeds under the Influence of Weed Control. *Indian J. Agric. Res.* **2006**, *40*, 86–91.
35. Srinivasarao, C.; Venkateswarlu, B.; Lal, R. Long-Term Effects of Soil Fertility Management on Carbon Sequestration in a Rice-Lentil Cropping System of the Indo-Gangetic Plains. *Soil Sci. Soc. Am. J.* **2012**, *76*, 167–178. [CrossRef]
36. Lal, R. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability* **2015**, *7*, 5875–5895. [CrossRef]
37. Walkley, A.; Black, I.A. An Examination of the Digestion Method for Determining Soil Organic Matter and a Proposed Modification of the Chromic Acid Titration Method. *Soil Sci.* **1934**, *1*, 29–38. [CrossRef]
38. Subbaiah, V.V.; Asija, G.K. A Rapid Procedure for Utilization of Available Nitrogen in Soil. *Curr. Sci.* **1956**, *26*, 258–260.
39. Olsen, S.R. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*; United States Department of Agriculture: Washington, DC, USA, 1954.
40. Nelson, L.; Heidel, H. *Soil Analysis Methods as Used in the Iowa State College Soil Testing Laboratory*; Iowa State College, Agronomy Department: Ames, IA, USA, 1952.
41. Steel, R.G.D.; Torrie, J.H.; Dickey, D.A. *Principles and Procedures of Statistics: A Biometric Approach*, 3rd ed.; McGraw Hill Book Co. Inc.: New York, NY, USA, 1997.
42. Wang, X.B.; Cai, D.X.; Hoogmoed, W.B.; Oenema, O.; Perdok, U.D. Developments in Conservation Tillage in Rainfed Regions of North China. *Soil Till. Res.* **2007**, *93*, 239–250. [CrossRef]

43. Layek, J.; Das, A.; Mitran, T.; Nath, C.; Meena, R.S.; Yadav, G.S.; Shivakumar, B.G.; Kumar, S.; Lal, R. Cereal + Legume Intercropping: An Option for Improving Productivity and Sustaining Soil Health. In *Legumes for Soil Health and Sustainable Management*; Springer: Singapore, 2018; pp. 347–386.
44. Choudhary, R.; Singh, P.; Sidhu, H.S.; Nandal, D.P.; Jat, H.S.; Jat, M.L. Evaluation of Tillage and Crop Establishment Methods Integrated with Relay Seeding of Wheat and Mungbean for Sustainable Intensification of Cotton-Wheat System in South Asia. *Field Crops Res.* **2016**, *199*, 31–41. [CrossRef]
45. Bessam, F.; Mrabet, R. Long-Term Changes in Soil Organic Matter under Conventional Tillage and No-Tillage Systems in Semiarid Morocco. *Soil Use Manag.* **2003**, *19*, 139–143. [CrossRef]
46. Mitchell, J.; Shrestha, A.; Mathesius, K.; Scow, K.; Southard, R.; Haney, R.; Schmidt, R.; Munk, D.; Horwath, W. Cover Cropping, and no-Tillage Improve Soil Health in an Arid Irrigated Cropping System in California's San Joaquin Valley, USA. *Soil Tillage Res.* **2017**, *165*, 325–335. [CrossRef]
47. Bhatt, R.; Kukal, S. Delineating Soil Moisture Dynamics as Affected by Tillage in Wheat, Rice and Establishment Methods of Rice during Intervening Period. *J. Appl. Nat. Sci.* **2015**, *7*, 364–368. [CrossRef]
48. Qamar, R.; Ullah, E.; Saqib, M.; Javeed, H.M.R.; Rehman, A.; Ali, A. Influence of Tillage and Mulch on Soil Physical Properties and Wheat Yield in Rice-Wheat Systém. *West Afr. J. Appl. Ecol.* **2015**, *23*, 21–38.
49. Nawar, A.I.; Fraihat, A.; Khalil, A.H.; El-Ela, A.M.A. Response of Faba Bean to Tillage Systems Different Regimes of NPK Fertilization and Plant Interspacing. *Int. J. Agric. Biol.* **2010**, *12*, 606–610.
50. Bedoussac, L.; Justes, E. Dynamic Analysis of Competition and Complementarity for Light and Use to Understand the Yield and the Protein Content of a Durum Wheat-Winter Pea Intercrop. *Plant. Soil.* **2010**, *330*, 37–54. [CrossRef]
51. Paul, B.K.; Vanlauwe, B.; Ayuke, F.; Gassner, A.; Hoogmoed, M.; Hurisso, T.T.; Pulleman, M.M. Medium-Term Impact of Tillage and Residue Management on Soil Aggregate Stability, Soil Carbon and Crop Productivity. *Agric. Ecosyst. Environ.* **2013**, *164*, 14–22. [CrossRef]
52. Rajpoot, S.K.; Rana, D.S.; Choudhary, A.K. Bt-Cotton–Vegetable-Based Intercropping Systems as Influenced by Crop Establishment Method and Planting Geometry of Bt-Cotton in Indo-Gangetic Plains Region. *Curr. Sci.* **2018**, *115*, 516–522. [CrossRef]
53. Rahman, M.H.; Ahmad, I.; Wang, D.; Fahad, S.; Afzal, M.; Ghaffar, A.; Saddique, Q.; Khan, M.A.; Saud, S.; Hassan, S.; et al. Influence of semi-arid environment on radiation use efficiency and other growth attributes of lentil crop. *Environ. Sci. Pollut. Res.* **2021**, *28*, 13697–13711. [CrossRef] [PubMed]
54. Dhima, K.V.; Lithourgidis, A.S.; Vasilakoglou, I.B.; Dordas, C.A. Competition Indices of Common Vetch and Cereal Intercrops in Two Seeding Ratio. *Field Crops Res.* **2007**, *100*, 249–256. [CrossRef]
55. Rahman, M.H.; Ahmad, A.; Wang, X.; Wajid, A.; Nasim, W.; Hussain, M.; Ahmad, B.; Ahmad, I.; Ali, Z.; Ishaque, W.; et al. Multi-Model Projections of Future Climate and Climate Change Impacts Uncertainty Assessment for Cotton Production in Pakistan. *Agric. For. Meteorol.* **2018**, *253*, 94–113. [CrossRef]
56. Ahmad, S.; Ghaffar, A.; Rahman, M.H.U.; Hussain, I.; Iqbal, R.; Haider, G.; Khan, M.A.; Ikram, R.M.; Hussnain, H.; Bashir, M.S. Effect of Application of Biochar, Poultry and Farmyard Manures in Combination with Synthetic Fertilizers on Soil Fertility and Cotton Productivity under Arid Environment. *Commun. Soil Sci. Plant Anal.* **2021**, *52*, 2018–2031. [CrossRef]
57. Rahman, M.H.; Ahmad, A.; Wajid, A.; Hussain, M.; Rasul, F.; Ishaque, W.; Islam, M.A.; Shelia, V.; Awais, M.; Ullah, A.; et al. Application of CSM-CROPGRO-Cotton Model for Cultivars and Optimum Planting Dates: Evaluation in Changing Semi-Arid Climate. *Field Crop. Res.* **2019**, *238*, 139–152. [CrossRef]
58. Rahman, M.H.U.; Ahmad, A.; Wajid, A.; Akhtar, J.; Hoogenboom, G.; Hussain, M. Estimation of Temporal Variation Resilience in Cotton Varieties Using Statistical Models. *Pak. J. Agric. Sci.* **2016**, *53*, 787–807.
59. Rahman, M.H.U.; Ahmad, I.; Ghaffar, A.; Haider, G.; Ahmad, B.; Tariq, M.; Nasim, W.; Rasul, G.; Fahad, S.; Ahmad, S.; et al. *Climate Resilient Cotton Production System: A Case Study in Pakistan*; Springer: Singapore, 2020; pp. 447–484. [CrossRef]
60. Manzoor, S.; Habib-Ur-Rahman, M.; Haider, G.; Ghafoor, I.; Ahmad, S.; Afzal, M.; Nawaz, F.; Iqbal, R.; Yasin, M.; Haq, T.U.; et al. Biochar and Slow-Releasing Nitrogen Fertilizers Improved Growth, Nitrogen Use, Yield, and Fiber Quality of Cotton under Arid Climatic Conditions. *Environ. Sci. Pollut. Res.* **2021**, *29*, 13742–13755. [CrossRef]
61. Majid, M.; Ali, M.; Shahzad, K.; Ahmad, F.; Ikram, R.M.; Ishtiaq, M.; Alaraidh, I.A.; Al-Hashimi, A.; Ali, H.M.; Zarei, T.; et al. Mitigation of Osmotic Stress in Cotton for the Improvement in Growth and Yield through Inoculation of Rhizobacteria and Phosphate Solubilizing Bacteria Coated Diammonium Phosphate. *Sustainability* **2020**, *12*, 10456. [CrossRef]