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Root System Architecture and Symbiotic Parameters of Summer Mung Bean (*Vigna Radiata*) under Different Conservation Agriculture Practices

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Abstract: Root system architecture plays a vital role in plant growth, development, and adaptation by absorbing water and nutrients and providing mechanical support for growing plants. Unfortunately, little information is available in the literature on the root dynamics of summer mung bean under conservation agriculture conditions. In this study, field experiments were conducted during the summer seasons of two consecutive years (2020 and 2021) to investigate the root system dynamics of summer mung bean under different conservation agriculture practices. The highest stem and system width, depth to width length, number of nodal roots, taproot diameter, secondary root length (both right and left) of summer mung bean were recorded in the Soybean (permanent bed; PB)-Wheat(PB)-Summer mung (PB)(+Residual; +R) based cropping systems, followed by Maize(PB)-Wheat(PB)-Summer mung (PB)(+R), while, the lowest values of above parameters were recorded in the Puddled Transplanted Rice–Conventional till (PTR-CT)Wheat-Summer mung (-R). Further, the pod length, number of seeds per pod, number of pods per plant, seed yield and symbiotic parameters (including number of nodules per plant, leghaemoglobin content) and root dry weight were recorded highest in Soybean (PB)-Wheat (PB)-Summer mung (PB)(+R). Interestingly, the yield of summer mung bean increased around 13.4–29.5% when residues were retained on the soil surface with treatments involving residual removal. The soil dehydrogenase enzyme activity increased significantly under Soybean (PB)-Wheat (PB)-Summer mung (PB)(+R) based cropping system as compared to PTR-CT Wheat-Summer mung (-R). In addition, the number of pods per plant exhibited a significantly positive correlation with yield during both crop seasons. Overall, this study suggests that the inclusion of summer mung in soybean-based cropping systems may substantially improve the root architecture and soil quality and increase crop yield under conservation agriculture.

Keywords: root; residues; symbiotic; yield; conservation agriculture

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1. Introduction

The root system architecture is a critical trait that plays a vital role in soil evaporation and water transport, and improves productivity in water-stressed conditions. Under drought and heat stress conditions, the deep and proliferating root system helps extract adequate water and nutrients from the deeper layers of the soil [1,2]. Shovelomics is an easy, robust, and inexpensive method for assessing plant roots and their efficient responses to different stresses. An excellent example represents the roots of legumes with extensive thickening able to extract soil water from deep grounds [3]. Significant differences exist between the legumes and grasses in secondary growth and the embryonic root system. In the case of crops grown in the field, the primary root is not developed properly; hence, the hypocotyls (nodal) roots take up nutrients from the deeper soil profile [4]. The root design of field-excavated root crown was recently measured using a Digital Imaging of Root Traits automated image processing method (DIRT). DIRT is a computer-assisted image processing program designed to quantify and differentiate crop root morphologies. For over 70 DIRT traits, it may be unbiased and automated. The key aim of this analysis was to consider the effects of various crop residues on previous crops and see RSA's effects on various cropping systems.

Legume inclusion in dominant cropping systems and adding residues lower the soil moisture loss while also improving soil organic carbon (SOC) and biophysical characteristics can have several advantages including those associated with life present or those associated with legume residues effects [5,6]. Therefore, it is obligatory to identify the sustainable intensification options of the rice-wheat cropping system (RWCS) using short duration summer legumes, i.e., summer mung or to diversify the RWCS with alternative cropping systems [7]. The legume pulses have been chosen for production in Asian and African countries for decades because they have the natural ability to restore soil fertility and maintain soil consistency. They are quite potent in soil minerals uptake and soil fertility improvement [8]. Crop leftovers, particularly legume residues, should be used to the fullest extent possible to improve soil fertility [9]. Since the dawn of civilisation, grain legumes (pulse crops) have been used in agricultural systems [10]. Summer mung (*Vigna radiata* L.), often known as summer green gram, is a good choice for RWCS because of its short growing season. The high protein edible seeds of the mungbean are advantageous over other crops. Their high nutrition value is advantageous over other pulses because of its high nutritional quality, digestion, and anti behaviour [11]. Summer mung integration in RWCS increases overall system productivity as well as cereal component crop productivity (rice and wheat), primarily when used for a long time [12]. Summer mung in the RWCS had a comparable beneficial impact on SOC in Mollisols and Inceptisols of Indo-Gangetic plains (IGP) [13]. Planting a short-duration mung following wheat and absorbing their residues in the next rice, according to [14], rendered the RWCS highly profitable, favourable, soil-restorative, and more sustainable than conventional systems.

A cropping system is defined as the cropping pattern and management to derive benefits from a given resource base under a specific environmental condition. These include crop area, crop biomass, economic yield, crop rotation, crop calendar, time, and spread of sowing and harvest. Crop production systems have shifted to cereal-based farming systems; however, this has raised concerns about soil degradation and crop yield reductions [15,16]. The declining yield in cereal-based cropping systems is the utmost important factor to be considered. It has caused nutritional imbalances in the soil environment, rendering crop production systems unsustainable [17]. The rice-wheat cropping system is one of the most important cereal-cereal cycles for satisfying South Asia's food needs. However, years of using the technique along the same farm have resulted in soil health loss, raising concerns about its long-term viability [18,19].

Furthermore, the biological nitrogen fixation inputs boost soil microbiology while reducing N_2O emissions [20]. A protocol is recommended based on these findings. Despite the fact that many studies have been published on the impact of crop residues management on agronomic productivity and economic profitability, a comprehensive evaluation of conservation-agriculture-based intensification systems in general and lacking info on summer mung root system architecture (RSA) in various cropping systems. Therefore, the objective of this research was to investigate root dynamic, symbiotic parameters and yield of summer mung bean under conservation agriculture-based practices in irrigated sandy loam elliptic soil in north-western India. A final research was undertaken to evaluate visual trait scores and manual traits.

2. Material Method

2.1. Experimental Site

The field experiments were conducted for two consecutive years (2020 and 2021) under normal conditions at the Punjab Agricultural University, Ludhiana, India. Ludhiana is situated at 30°54 N latitude and 75°56 E longitude, at 247 metres above sea level. During the summer season of the year 2020, temperature ranged from 11.14 to 42.09 °C, whereas it ranged from 5.8 to 39.4 °C during the summer season of the year 2021 (recorded during 16th and 25th standard meteorological week). Total rainfall received during crop season was 72.4 mm for 2020 and 126.8 mm for 2021. The soil of the experimental field was sandy loam in texture, low in available N (181.9 kg/ha), medium in available P (21.2 kg/ ha) and K (208.6 kg/ha) and alkaline in reaction (pH 7.31).

2.2. Experimental Design and Treatments Details

The field experiments were conducted in a randomized complete block design (RCBD) with four replications and six treatments. The details of treatments are given in Table 1.

Table 1. An overview of treatments.

Treatments	Cropping System	Treatment Codes	Residue Management
T_1	Puddled transplanted rice—Conventional till wheat—summer mung	PTR—CTW—SM	All residues removed
T_2	Puddled transplanted rice—Happy seeder wheat-summer mung (ZT)	PTR—HSW—SM	20–25% Wheat residue-100% SM residue-100% rice residue
T_3	Fresh bed maize (FB)—Conventional till wheat-summer mung	FBM—CTW—SM	All residues removed
T_4	Permanent bed maize (PB)—Permanent bed wheat (PB)—Permanent bed summer mung(PB)	PBM—PBW—PBSM	20–25% Wheat residue-100%SM residue-50–60% Maize residue
T_5	Fresh bed soybean (FB)—Conventional till wheat-summer mung	FBS—CTW—SM	All residues Removed
T_6	Permanent bed soybean (PB)—Permanent bed wheat (PB)—Permanent bed summer mung (PB)	PBS—PBW—PBSM	20–25% Wheat residue-100% SM residue -100 % soybean

2.3. Crop Management

The experiment was started in the *Rabi* season of the year 2018–2019. Wheat, and summer mung were used as zero cycle crops, and then all treatments were applied in the next crop, *kharif*. A week before planting, vigorous pre-sowing irrigation (75 mm depth) was applied as per recommended irrigation package for the crop. The summer mung variety (i.e., SML 832) used for the present study has erect plants, determinate growth habit with medium stature and matures in around 61 days. The crop geometry for summer mung was 22.5 cm × 7 cm (showing a plant density of 6.34 lakhs plants ha^{-1}). The irrigation was applied at critical growth phases through flood method in conventional till treatments and soil matric potential (−40 ±1 kpa) based irrigation scheduling for the permanent bed treatments. The Summer mung bean seeds were treated with the captan (fungicide) @ 3 kg ha^{-1} seed to protect the crop against fungal diseases. The fertiliser application involved 12.5 kg ha^{-1} N and 40 kg ha^{-1} P_2O_5, the entire amount of nitrogen and phosphorus was applied as basal application. The supply of nitrogen was made through urea (46% N) and phosphorus was supplied through single super phosphate

(16% P_2O_5). For weed control, a pre-emergence herbicide (pendimethalin) @ 2.5 l ha^{-1} was applied, and one hand weeding was performed 20 days after sowing. The crop was sprayed with 3.75 L of Dursban 20 EC (chlorpyriphos) per acre by dissolving in 250 litres of water to suppress the tobacco caterpillar. All the recommended cultural operations other than the treatments were followed to raise the crop.

2.4. Data Recording

The number of nodules per plant was counted on six plants chosen at random in different treatments. Plants were gently removed from the soil using a sieve and large earthen ball sand. The roots were gently rinsed in running water, the nodules were removed, and the number of nodules per plant was counted. Wilson's and Reisenauer's method (1963) [21] was used to determine the content of leghaemoglobin, bold, and pink nodules at 50 days after sowing (DAS). Roots from six randomly selected plants in each plot were collected and sun-dried after washing in running tap water using a sieve. Then they were oven-dried at 60 °C until they reached a consistent weight and then their weights (mg/plant) were recorded. Crops were harvested manually according to residues protocols, and data was recorded on the following parameters: pod length, number of seeds per pod, number of pods per plant, grain, and straw yield.

2.5. Root Phenotyping following the Shovelomics Techniques

Field root phenotyping using Shovelomics techniques: Excavate and wash roots; the root crowns are excavated in approximately two stages 30 DAS and before harvest. Photograph root crowns using a Canon EOS 70D DSLR camera mounted to an aluminium frame wrapped in black cloth. Still, the root crowns were imaged with an open front to eliminate directional and optimize diffuse illumination. Roots should be placed with a circular scale of 42 mm on a matt black vinyl backdrop and a white sample ID sticker. First, the whole root crown was photographed, then divided into the primary shoot and tillers. Take measurements (ImageJ). Images are evaluated using an ObjectJ plugin project for ImageJ and all characteristics are analysed, i.e., stem distance, system width, depth to width length, taproot diameter, calculated number of roots and nodal root lengths and the attributing characteristics of the yield (Table 2).

Table 2. Description of different roots recorded.

S.no	Trait	Treatment Codes	Method Used	Description
1	Stem width	ST_W	Imagej software	stem width/diameter at soil level
2	System width	SYS_W	Imagej software	Whole root system width at the mid of root system of plant
3	Depth to width length	DEP_W	Imagej software	Length of centre between stem width to system width
4	Nodal root number	NRN	Count	No. of primary roots in the plant
5	Tap root diameter 10 cm	TD	Caliper	tap diameter 10 below soil surface
6	Secondary root length right	SRL right	Caliper, Imagej	-
7	Secondary root length left	SRL left	Caliper, Imagej	-

2.6. Statistical Analysis

The data were analysed in randomized complete block design with the help of a statistical analysis system (SAS Institute, Cary, NC, USA) [22] and R software to determine the significance among different treatments and image analysed with the help of Imagej and DIRT (Digital Imaging of Root Traits) software for roots characters. The differences between treatment means were composed using Tukey's HSD test at $p < 0.05\%$. To eliminate biases, Principal Component Analysis (PCA) was used. Variables with high factor loading values in each Principal Component (PC) were regarded as the best representations of system attributes.

3. Result

Effect of conservation agriculture (CA) practices on root system architecture (RSA).

3.1. Effect of CA on Root Parameters at 30 DAS

The highest stem width (135.8–155.8 mm), system width (2504.5–2704.5 mm), depth to width length (1324.8–1524.8 mm), number of nodal roots (20–22), taproot diameter (68.4–78.3 mm), secondary root length right (1233.4–1433.4 mm) and secondary root length left (1749.5–1999.5) were recorded in T_6 (Table 3). Stem width and taproot diameter during the year 2020, T_4 and T_2 remained at par with T_6, whereas in the year 2021, T_2, T_3, T_4, and T_5 were significantly lower than T_6 for stem width, while during the year 2021, T_2, T_4, and T_5 were significantly lower than T_6 for tap root diameter. The system width ranged from 730 to2704 mm showing significant differences among the treatments. The increment was 1.86 and 1.71 folds for depth to width under T_6 compared to T_1 during 2020 and 2021, respectively. The nodal root number ranged from 9 to 22 with the highest observed in T6 followed by T_4. The secondary root length right ranged from 816 to 1433 mm with no significant differences among the treatments (except T_6). The secondary root length left ranged from 584 to 1999 during both years.

Table 3. Effect of different conservation agriculture and conventional till management practices on root parameters of summer mung bean (at 30 days after sowing) in different cropping systems.

Treatments	Stem Width (mm)		System Width (mm)		Depth to Width (mm)		Nodal Root Number		Tap Root Diameter (mm)		Secondary Root Length Right (mm)		Secondary Root Length Left (mm)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
T_1	70.7 ^{c}	90.7 ^{c}	730.2 ^{d}	930.2 ^{d}	462.02 ^{c}	562.0 ^{d}	9 ^{c}	11 ^{e}	19.3 ^{b}	29.3 ^{c}	816.1 ^{b}	1016.1 ^{b}	584.8 ^{c}	759.8 ^{d}
T_2	105.4 ^{ab}	125.4 ^{b}	1455.4 ^{bc}	1655.5 ^{bc}	1100.2 ^{ab}	1300.2 ^{bc}	15 ^{b}	16 ^{bc}	40.2 ^{ab}	49.7 ^{b}	1004.0 ^{b}	1185.6 ^{b}	1428.5 ^{abc}	1628.5 ^{b}
T_3	99.2 ^{bc}	119.2 ^{b}	1366.7 ^{bcd}	1566.7 ^{c}	1073.5 ^{ab}	1273.5 ^{c}	11 ^{bc}	13 ^{d}	19.7 ^{b}	29.7 ^{c}	955.1 ^{b}	1130.1 ^{b}	943.0 ^{abc}	1093 ^{c}
T_4	105.8 ^{ab}	125.8 ^{b}	1609.5 ^{b}	1809.5 ^{b}	1277.4 ^{a}	1477.4 ^{ab}	15 ^{b}	17 ^{b}	42.2 ^{ab}	50.2 ^{b}	1035.6 ^{b}	1204.0 ^{b}	1471.7 ^{b}	1696.7 ^{b}
T_5	96.1 ^{bc}	121.6 ^{b}	887.1 ^{cd}	1037.1 ^{d}	631.5 ^{bc}	706.5 ^{d}	13 ^{bc}	15 ^{c}	35.7 ^{b}	45.7 ^{b}	818.6 ^{b}	1018.6 ^{b}	717.9 ^{bc}	867.9 ^{cd}
T_6	135.8 ^{a}	155.8 ^{a}	2504.5 ^{a}	2704.5 ^{a}	1324.8 ^{a}	1524.8 ^{a}	20 ^{a}	22 ^{a}	68.4 ^{a}	78.3 ^{a}	1233.4 ^{a}	1433.4 ^{a}	1749.5 ^{a}	1999.5 ^{a}

Note: T_1 = Puddled transplanted rice (PTR)-conventional till (CT) Wheat-Summer mung) (−R or completely removal residues), T_2 = PTR- Happy seeder Wheat-zero till summer mung (ZT) (+R or residues retention on the soil surface), T_3 = Fresh bed Maize (FB)-CT Wheat -Summer mung (−R), T_4 = Permanent bed Maize (PB)-Wheat (PB)-Summer mung (PB) (+R), T_5 = Soybean (FB)-Wheat (CT)-Summer mung (−R) and T_6 = Soybean (PB)-Wheat (PB)-Summer mung (PB) (+R). Similar lowercase letter(s) within a column in a given year represent no significant statistical difference at 0.05 level of probability using Tukey's HSD test.

3.2. Effect of CA on Root Parameters Recorded before Harvesting

Data on different root traits (Table 4) indicate that conservation agriculture practices significantly increased the root traits *viz.*, stem width, system width, number of nodal roots, taproot diameter, secondary root length right and left than conventional practices (T_1). The highest stem width (122.1–212.8 mm), system width (2212.4–2339.4 mm), depth to width length (1305.1–1505 mm), number of nodal roots (25–30), taproot diameter (71.7–81.7 mm), secondary root length right (1616.6–1816.6 mm) and secondary root length left (1717.6–1917.6) were recorded in T_6. In the case of stem width, during the year 2020, T_4 remained at par with T_6, whereas in 2021, T_4 was significantly different from T_6. The system width ranged from 1338 to 2339 mm, and T_2, T_3, T_4, and T_5 did not differ substantially during the year 2020, while in the year 2021, T6 remained at par with each other T_4. The increment in-depth to width under T_6 compared to control (T_1) was 133% and 120% during 2020 and 2021, respectively. The nodal root number ranged from 8 to 30 with the highest nodal root number observed in T_6 followed by T_4 and T_2. The increment in taproot diameter under T_6 compared to control was the tune of 478% and 264% during 2020 and 2021, respectively. The secondary root length right ranged from 610 to 1816 mm and T_6

remained at par with T4 during both years. The secondary root length left ranged from 693 to 1917 mm.

Table 4. Effect of different conservation agriculture and conventional till management practices on root parameters of summer mung bean (before harvesting) in different cropping systems.

Treatments	Stem Width(mm)		System Width(mm)		Depth to Width(mm)		Nodal Root Number		Tap Root Diameter(mm)		Secondary Root Length Right(mm)		Secondary Root Length Left(mm)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
T_1	64.4 ^{d}	74.4 ^{d}	1338.4 ^{b}	1510.8 ^{d}	558.7 ^{b}	683.7 ^{c}	8 ^{d}	11 ^{d}	12.4 ^{c}	22.4 ^{e}	610.3 ^{d}	785.3 ^{d}	693.8 ^{b}	771.2 ^{e}
T_2	95.5 ^{bc}	106.9 ^{c}	1914.4 ^{ab}	2087.4 ^{abc}	930.7 ^{b}	1167.5 ^{b}	19 ^{b}	22 ^{b}	36.6 abc	46.6 ^{c}	1416.9 ^{b}	1604.9 ^{b}	1437.0 ^{ab}	1637.0 ^{b}
T_3	69.7 ^{d}	84.2 ^{cd}	1790.3 ^{ab}	1815.3 ^{cd}	901.5 ^{bc}	1104.6 ^{b}	10 ^{cd}	13 ^{cd}	26.3 ^{bc}	35.5 ^{d}	824.3 ^{c}	1024.3 ^{c}	863.1 ^{b}	1038.1 ^{d}
T_4	101.9 ^{ab}	132.1 ^{b}	2008.1 ^{ab}	2233.1 ^{ab}	972.0 ^{ab}	1172.0 ^{b}	21 ^{b}	24 ^{b}	52.9 ^{ab}	62.9 ^{b}	1511.0 ab	1641.9 ab	1498.6 ^{ab}	1748.6 ab
T_5	72.4 ^{cd}	105.5 ^{c}	1730.4 ^{ab}	1905.4 ^{bc}	917.5b ^{c}	1076.5 ^{b}	12 ^{c}	15 ^{c}	14.5 ^{c}	24.7 ^{e}	725.9 ^{cd}	925.9 ^{cd}	1131.0 ^{ab}	1331.0 ^{c}
T_6	122.1 ^{a}	212.8 ^{a}	2212.4 ^{a}	2339.4 ^{a}	1305.1 ^{a}	1505 ^{a}	25 ^{a}	30 ^{a}	71.7 ^{a}	81.7 ^{a}	1616.6 ^{a}	1816.6 ^{a}	1717.6 ^{a}	1917.6 ^{a}

Note: T_1 = Puddled transplanted rice (PTR)-conventional till (CT) Wheat-Summer mung) (−R or completely removal residues), T_2 = PTR- Happy seeder Wheat-zero till summer mung (ZT) (+R or residues retention on the soil surface), T_3 = Fresh bed Maize (FB)-CT Wheat -Summer mung (−R),T_4 = Permanent bed Maize (PB)- Wheat (PB)-Summer mung (PB) (+R),T_5 = Soybean (FB)-Wheat (CT)-Summer mung (−R)andT_6 = Soybean (PB)-Wheat (PB)-Summer mung (PB)(+R). Similar lowercase letter(s) within a column in a given year represent no significant statistical difference at 0.05 level of probability using Tukey's HSD test.

3.3. Yield and Component Traits

The data seed yield and other component traits were recorded at harvest time (Table 5). T6 exhibited the highest pod length (8.03–8.22 cm), number of seeds per pod (10.75–12) and number of pods per plant (32–35). In the year 2020, the highest pod length, no. of seeds/pod and no of pod per plants were observed in $T_{6,}$ which remained statistically on par with T_2 and $T_{4,}$ whereas, in the year 2021, the highest pod length, no. of seeds per pod and no of pod per plants were recorded in T_6 which was significantly different from T_2. The increment in number of pods per plant and number of seeds per pod were 64.10 & 71.4% and 61.29 & 74.6% for T6 compared to control (T1) during 2020 and 2021, respectively.

Table 5. Effect of different conservation agriculture and conventional till management practices on yield attributes and yield of summer mung bean during 2020 and 2021 in different cropping systems.

Treatments	Pod Length(cm)		No. of Pods/Plant		No. of Seeds/Pod		Yield (kg/ha)	
	2020	2021	2020	2021	2020	2021	2020	2021
T_1	6.4 ^{c}	6.6 ^{c}	19.5 ^{c}	21.7 ^{d}	6.3 ^{b}	7.1 ^{c}	755 ^{e}	812 ^{e}
T_2	7.4 ^{ab}	7.6 ^{ab}	26.0 ^{abc}	30.5 ^{b}	8.5 ^{ab}	10.0 ^{b}	888 ^{bc}	918 ^{bc}
T_3	6.9b ^{c}	7.1 ^{bc}	22.5 ^{bc}	25.8 ^{c}	6.8 ^{b}	8.2 ^{c}	807 ^{d}	847 ^{d}
T_4	7.7 ^{a}	7.9 ^{ab}	28.0 ^{ab}	31.0 ^{b}	10.5 ^{a}	12.3 ^{a}	905 ^{b}	950 ^{b}
T_5	6.9 ^{bc}	7.1 ^{bc}	23.2 ^{bc}	25.5 ^{c}	6.5 ^{b}	8.1 ^{c}	855 ^{c}	888 ^{c}
T_6	8.0 ^{a}	8.2 ^{a}	32.0 ^{a}	35.0 ^{a}	10.8 ^{a}	12.4 ^{a}	978 ^{a}	1012 ^{a}

Note: T_1 = Puddled transplanted rice (PTR)-conventional till (CT) Wheat-Summer mung) (−R or complete removal of residues), T_2 = PTR- Happy seeder Wheat-zero till summer mung (ZT) (+R or residues retention on the soil surface), T_3 = Fresh bed Maize (FB)-CT Wheat –Summer mung (−R), T_4 = Permanent bed Maize (PB)- Wheat (PB)-Summer mung (PB) (+R), T_5 = Soybean (FB)-Wheat (CT)-Summer mung (−R) and T_6 = Soybean (PB)-Wheat (PB)-Summer mung(PB)(+R). Similar lowercase letter(s) within a column in a given year represent no significant statistical difference at 0.05 level of probability using Tukey's HSD test.

Significant improvement in summer mung yield was observed when residues from the previous crop were retained in the soil (Figure 1). The highest seed yield was 978 kg/ha, and 1012 kg/ha was recorded in $T_{6,}$ which was a statistically significant difference with T_2 (888 kg/ha and 918 kg/ha) and T_4 (905 and 950 kg/ha) during both the year but treatment T_2 was at par with T_4. The increment in seed yield under T6 compared to control (T1) was 29.5% and 24.6% during 2020 and 2021, respectively. The minimum seed yield was noticed in T_1 (755 and 812 kg/ha) for both seasons. The treatment T_6 showed maximum seed yield, which was significantly superior to the remaining treatments.

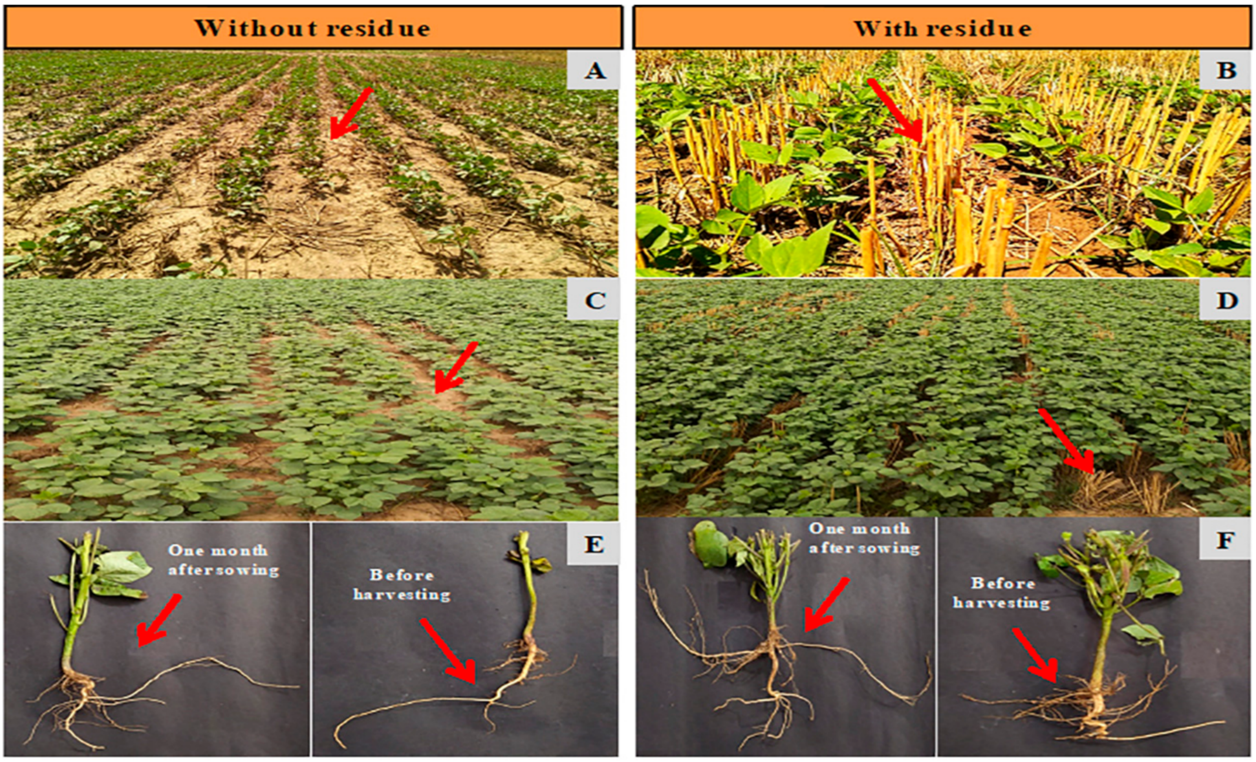


Figure 1. Different growth stage of summer mung without residue (**A**,**C**,**E**) and with residue (**B**,**D**,**F**): Early growth stage 15 DAS (**A**,**B**), crop growth stage at 30 DAS (**C**,**D**) and root study at 30 DAS and before harvesting (**E**,**F**).

3.4. Symbiotic Parameters and Root Dry Weight

Data on number of nodules per plant, the weight content of fresh leghaemoglobin nodule, and the root dry weight of summer mung recorded before harvesting are presented in Table 6. In both the years, treatment T6 showed the highest number of nodules per plant of summer mung, which was statistically significant with treatment T_4 but statistically at par with T_2. In the second year, the content of leghaemoglobin of summer mung was recorded highest in treatment $T_{6,}$ which was significantly different from the treatments T_4 and T_2. Still treatment T_2 was statistically on par with T_4, and recorded the lowest leghaemoglobin content in T_5. Dry root weight increased to 50 DAS in the second year, then declined somewhat at maturity. The highest dry root weight was observed in T6, followed by T_4, T_2, T_3, and $T_{1,}$ whereas the lowest was observed in T_5 (Table 6). The DHA ranged from 29.4 to 51.3 µg TPF g^{-1} soil 24 h^{-1}, highest DHA was recorded in $T_{6,}$ followed by T_2 and T_4. Compared to T_1, DHA was 58.84% higher in T_6 and 31.29% higher in T_4.

3.5. Principal Component Analysis

The principal component analysis is a technique for identifying minimum data sets where only the variables with high loading factors were selected from each PC. This analysis may be used to choose the optimal genotypes for breeding. Figure 2 represents the variance on each axis, the percentage of total variance representing the coefficients used in weighted sum (eigenvectors or loadings) [23]. The first two principal components had more than 1 eigenvalue. These two principal components explained 97.4 and 1.6%, respectively, constituting 98.9% of the total variation for 15 different traits recorded in the year 2020. Whereas, in the year 2021, the first two principal components explained 92.9 and 5.45%, respectively, constituting 98.3% of the total variation for 15 different traits (Figure 2 and Table 7).

Table 6. Effect of different conservation agriculture and conventional till management practices on symbiotic parameters and root dry weight of summer mung bean (before harvesting) in different cropping systems.

Treatments	No of Nodules /Plant		Leghaemoglobin (mg/g)		Root Dry Weight (g)		DHA (μg TPF/g/24 h)	
	2020	2021	2020	2021	2020	2021	2019–2020	2020–2021
T_1	42.1 ^{c}	51.3 ^{a}	4.0 ^{bc}	4.5 ^{bc}	1.4 ^{c}	1.5 ^{d}	29.4 ^{d}	31.3 ^{e}
T_2	65.5 ^{ab}	76.2 ^{a}	4.2 ^{b}	4.7 ^{b}	2.0 ^{a}	2.7 ^{b}	36.8 ^{b}	40.5 ^{c}
T_3	38.2 ^{d}	47.7 ^{d}	3.8 ^{c}	4.3 ^{cd}	1.4 ^{c}	1.5 ^{d}	31.4 ^{c}	34.2 ^{d}
T_4	63.2 ^{b}	72.9 ^{b}	4.1 ^{b}	4.6 ^{b}	1.9 ^{b}	2.5 ^{c}	38.6 ^{b}	43.7 ^{b}
T_5	41.5 ^{c}	53.8 ^{c}	3.8 ^{c}	4.2 ^{d}	1.4 ^{c}	1.5 ^{d}	28.4 ^{d}	32.1 ^{e}
T_6	67.2 ^{a}	78.5 ^{a}	5.1 ^{a}	5.8 ^{a}	2.0 ^{a}	2.8 ^{a}	46.7 ^{a}	51.3 ^{a}

Note: DHA = Dehydrogenase enzyme activities; T_1 = Puddled transplanted rice (PTR)-conventional till (CT) Wheat-Summer mung) (−R or completely removal residues), T_2 = PTR-Happy seeder Wheat-zero till summer mung (ZT) (+R or residues retention on the soil surface), T_3 = Fresh bed Maize (FB)-CT Wheat -Summer mung (−R),T_4 = Permanent bed Maize (PB)- Wheat (PB)-Summer mung (PB) (+R), T_5 = Soybean (FB)-Wheat (CT)-Summer mung (−R) and T_6 = Soybean (PB)-Wheat (PB)-Summer mung (PB) (+R). Similar lowercase letter(s) within a column in a given year represent no significant statistical difference at 0.05 level of probability using Tukey's HSD test.

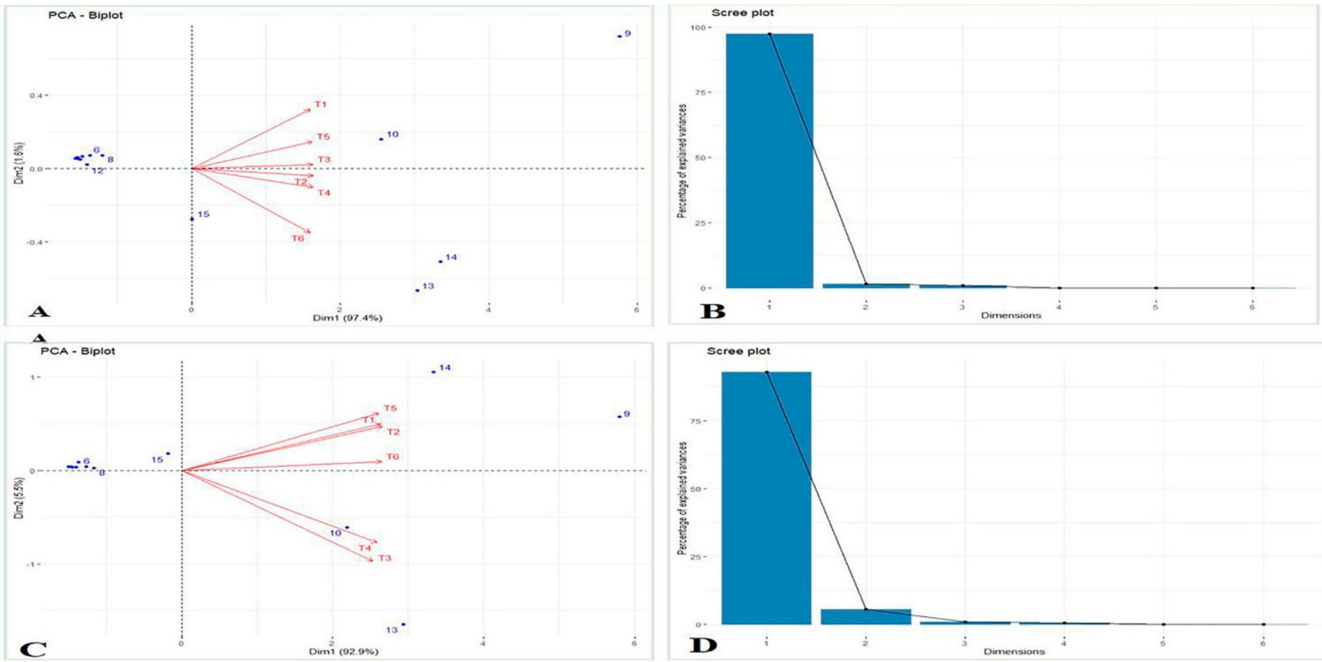


Figure 2. Principal component analysis during 2020 (**A**,**B**) and 2021 (**C**,**D**). Note: 1 = yield, 2 = pod length, 3 = no. of seeds/pod, 4 = root dry wt., 5 = leghaemoglobin content, 6 = no of pod per plant, 7 = stem width, 8 = system width, 9 = depth to width, 10 = nodal root number, 11 = tap root diameter, 12 = tap root diameter, 13 = SLR (Secondary root length left), 14 = SLL (Secondary root length left), 15 = seminal root length. T_1 = puddled transplanted rice (PTR)-conventional till (CT) Wheat-summer mung) (−R or completely removal residues), T_2 = PTR- Happy seeder Wheat-zero till summer mung (ZT) (+R or residues retention on the soil surface), T_3 = Fresh bed Maize (FB)-CT Wheat -summer mung (−R),T_4 = Permanent bed Maize (PB)- Wheat (PB)-summer mung (PB) (+R),T_5 = Soybean (FB)-Wheat (CT)-summer mung(−R) and T_6 = Soybean(PB)-Wheat(PB)-summer mung (PB) (+R).

Table 7. Eigenvalues, variance percentages, cumulative variances (%), and principal component analysis standard errors for both years.

	2020				2021			
PCA	**Eigen Value**	**Variance (%)**	**Cumulative Variance (%)**	**Standard Error**	**Eigenvalue**	**Variance (%)**	**Cumulative Variance (%)**	**Standard Error**
PF1	5.841	9.73	97.36	2.41	5.57	9.29	92.92	2.36
PF2	0.097	1.61	98.98	0.31	3.27	5.45	98.38	0.57
PF3	0.055	9.30	99.91	0.23	5.95	9.92	99.37	0.24
PF4	0.003	5.23	99.96	0.05	3.55	5.91	99.96	0.18
PF5	0.002	3.37	99.99	0.04	1.92	3.20	99.99	0.04
PF6	0.00002	3.92	100	0.004	2.51	4.18	100	0.005

Note: PF = Principal factor.

3.6. Correlation of Different Components with Yield

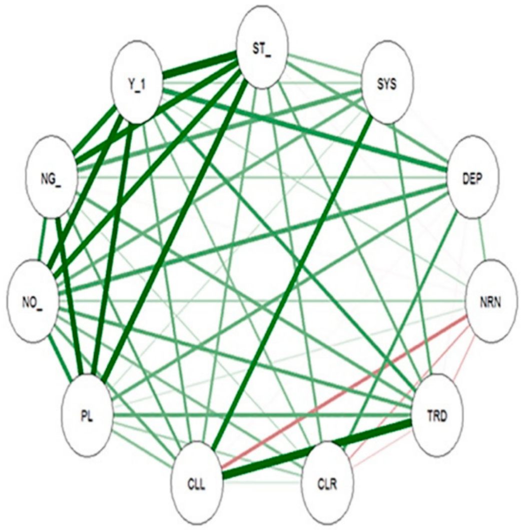
A correlation study helps to understand the relationship between major yield component traits. Correlations among the different traits are presented in Table 8 and Figure 3. The pod length (0.821), stem width (0.815) and number of pods per plant (0.798) had significant positive correlation with yield during the year 2020. Similarly in the year 2021, number of pods per plant (0.886), number of seeds per pod (0.785), and the nodal root number (0.753) showed a significant positive correlation with seed yield. The number of pods per plant exhibited substantial correlation with seed yield in both the years (Table 8 and Figure 3).

Table 8. Correlation coefficients among all possible combinations of different yield component traits recorded on summer mung before harvesting.

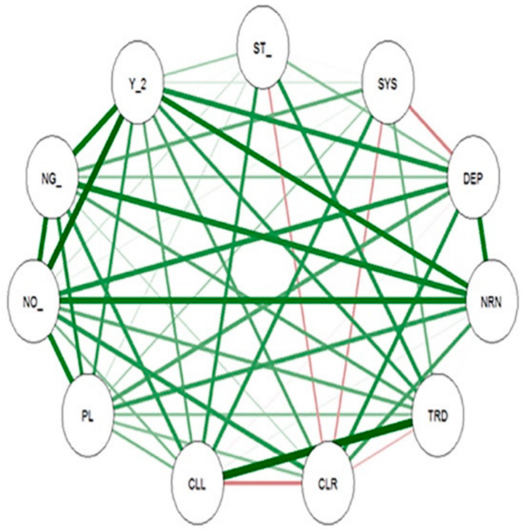
Traits	Years	SYS_W	DEP_W	NRN	TRD	SLR	SLL	PL	NO_POD	NG_P	Y
ST_W	2020	0.292	0.383	−0.063	0.391	0.384	0.364	0.772 **	0.715 **	0.733 **	0.815 **
	2021	0.033	0.324	0.026	0.592 **	−0.340	0.583 **	0.159	0.137	0.036	0.266
SYS_W	2020		−0.047	−0.003	0.432 *	−0.018	0.684 **	0.237	0.381	0.434 *	0.218
	2021		−0.400	−0.006	0.412 *	−0.344	0.578 **	0.259	0.114	0.455 *	0.131
DEP_W	2020			0.299	−0.073	0.469 *	−0.041	0.403	0.470 *	0.231	0.525 **
	2021			0.762 **	−0.022	0.616 **	−0.095	0.496 *	0.624 **	0.301	0.626 **
NRN	2020				−0.197	−0.243	−0.387	0.114	0.224	−0.038	0.185
	2021				0.036	0.523 **	0.112	0.542 **	0.750 **	0.717 **	0.753 **
TRD	2020					−0.133	0.797 **	0.419 *	0.430 *	0.394	0.494 *
	2021					−0.210	0.912 **	0.330	0.455 *	0.481 *	0.558 **
CLR	2020						0.116	0.230	0.322	0.178	0.304
	2021						−0.422 *	0.344	0.579 **	0.196	0.495 *
CLL	2020							0.291	0.398	0.423 *	0.413 *
	2021							0.372	0.369	0.578 **	0.473 *
PL	2020								0.551 **	0.814 **	0.821 **
	2021								0.732 **	0.660 **	0.567 **
NO_POD	2020									0.565 **	0.798 **
	2021									0.812 **	0.886 **
NG_P	2020										0.680 **
	2021										0.785 **

* Significant at 5% and ** Significant at 1% level of significance. Note: ST_W = Stem width, SYS_W = System width, DEP_W = Depth to width, NRN = Nodal root number, TRD = Tap root diameter, CLR/SLR = Secondary root length right, CLL/ SLL = Secondary root length left, PL = Pod length, NO_POD = No. of pods/plant, NG_P = No. of seeds/pod and Y = Yield (kg/ha).

Dark green colour shaded shows the strongly positively correlated to each other and shows significant difference for both the year. In light green colour shaded the positively correlated and it show no significant difference to each other and red colour line shows negative correlated and no significant difference each other.



(**A**)



(**B**)

Figure 3. Correlation analysis of summer mung during 2020-21 before harvest (**A**,**B**). **Note:** ST_ = Stem width, SYS = System width, DEP = Depth to width, NRN = Nodal root number, TRD = Tap root diameter, CLR/SLR = Secondary root length right, CLL/ SLL = Secondary root length left, PL = Pod length, NO_ = No. of pods/plant, NG = No. of seeds/pod and Y_1 and Y_2 = Yield (kg/ha).

4. Discussion

4.1. Effect of Conservation Agriculture Practices on Different Root Parameters

Improved root system architecture observed under conservation agriculture-based practices indicates that the retention of legume (summer mung and soybean) improved the soil organic matter, nitrogen, and phosphorus, and decreased the immobilization of nitrogen owing to lower carbon to nitrogen ratio and increased availability of nutrients to the plants. The straw application boosts the availability of macro and micronutrients and increases the soil organic matter and nitrogen stocks [24,25]. In the second year, T6 showed the most considerable increase in stem width (102.19%), depth to width length (39.80%), and nodal root (100%). The retention of crop residues under CA improved microbial biomass carbon and microbial biomass nitrogen, enhancing soil biological activities compared to conventional practices. [26]. In the second year to increase the 96.19% secondary root length (SRL) right, 44.07% secondary root length (SRL) left and 230.7% taproot diameter was recorded in T_6 concerning T_5 treatment to cropping systems with pulses having more exceptional soil carbon sequestration ability than mono-cropping. Previous studies have shown under conservation agriculture practices that roots mainly increase the number of soil macropores and promote the connectivity between soil pores, leading to changes in soil structure, soil macropores, soil water holding capacity, and water conductivity. Plant residues of pulses have a narrow C:N ratio, which helps in easy decomposition, mineralization, and increased wheat grain yield, as compared to no mulch [27,28]. Mulch created 40% larger root length densities in lower layers (>0.15 m) than no-mulch, owing to increased soil moisture conservation in deeper layers. Root exudates contain amino acids, sugars, and carboxylic acids, which act as attractants for beneficial microorganisms [29].

4.2. Seed Yield and Component Traits

The highest yield attributes of summer mung were recorded in conservation agriculture practices (T_6, T_4, and T_2) due to pulses content mineralizable-nitrogen being higher than the non-pulse crops or under uncultivated fallows. The yield of summer mung increased around 13.4–29.5% in residues retention (T_2, T_4 and T_6) on the soil surface as compared to without residues treatments (T_1, T_3 and T_5). It may be attributed to the retention of pulse crop residues on soil surfaces, leading to greater nutrient availability and increasing morphological traits. It could be because legumes provide a number of advantages, including N supply through biotic N fixation, improved nutrient availability through the deeper rooting, decreased compaction, higher SOC [30,31]. According to Sharma and Prasad [32], combined application of wheat residues and green manure (sesbania or mung bean) boosted crops grain output and agronomic N efficacy and improved the normally negative apparent N balances.

4.3. Symbiotic Parameters and Root Dry Weight and Dehydrogenase Activity

Symbiotic parameters and root dry weight being recorded at their highest values in conservation agriculture-based treatment might be due to the residues of pulse content being three times more nitrogen-rich than the cereal residues [33]. The retention of residues may increase soil quality, hydraulic conductivity, crop water supply capacities, nutrient availability, exchangeable cations, soil responsiveness, carbon sequestration, microbial biomass nitrogen and carbon activities, and species diving properties [34–38]. DHA was 58.84% in the present study, and 31.29% was higher in T_6 and T_4 than $T_{1,}$ respectively. Soil enzyme activity is positively connected with zero tillage and inversely correlated with CT [39,40] and it might be due to mixing of previous crops residue which was retained on the soil surface which increases the availability of labile carbon produced after decomposition of the previous year [41].

4.4. Principal Component Analysis (PCA) and Correlation

Most of the assessed variables were highest with treatment T_6 followed by T_4 (Figure 2). The most influential variables for the PC1 were varied yield, pod length and no. of seeds/pod and for the second principal component were secondary root length left seminal root length (Table 6). This suggests that continuous inclusion of C sources through preceding crop residue increased microbial activity as well as the availability of various microbial communities in the soil, nutrient availability, and rhizodeposition, all of which could be factors in increased soil carbon pools but also hydrolytic enzymatic activities. In the orthogonal space of PCA, [42]. Most of the studied variables (microbial biomass carbon and basal soil respiration) were more closely conjugated with organically managed soils than inorganically managed soils. This supports [38] an earlier finding that PCA clearly distinguished zero tillage with crop residues from CT without residue treatments. Correlation analysis revealed that the number of pods per plant correlated highly with yield during both seasons. Similar results were also reported by [43]. Dark green colour shaded shows the strong positive correllations to each other and the significant difference for both the seasons (Table 8 and Figure 3).

5. Conclusions

The current study revealed that Soybean (PB)-Wheat (PB)-Summer mung (PB)(+R) increased seed yield, symbiotic parameters, and root traits. The seed yield of summer mung under T6 was significantly 8.0–9.5% and 24.6–29.5% higher as compared to T4 and T1, respectively. Pod length, number of seeds/pod and secondary root length left were dominant indicators for assessing crop yield in this study under conservation agricultural-based sustainable practice than the conventional.

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