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Research Article

Technology Development with Zero Tillage and Stubble Residue Management for Sustainable Soil Health and System Productivity in Wheat-maize Cropping Pattern

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Abstract

Conventional farm operations comprising traditional soil tillage and burning stubble residues become the cause of concern for soil sickness threatening sustainable system productivity. Wheat and maize constituting one of the predominant cropping systems strive with the commitment of substantial contribution to the world food security front. A better understanding of these alarming issues insisted on us to explore 'Conservation Agriculture' practices designing a field experiment with tillage and crop residue management. The study from 2019 to 2022 derived phenomenal achievement with Zero Tillage (ZT) and Minimal Tillage (MT) in compliance with crop residue retention (+ R); while, the eventuality of stubble burning (- R) deteriorated soil health, especially with Conventional Tillage (CT). Results illustrated significantly higher system productivity (11.60 - 12.0 t ha^{-1}) in terms of wheat equivalent yield at (ZT+R) stands followed by those (11.34-11.64 t ha^{-1}) at (MT + R), significantly higher than those (10.52 - 10.59 t ha^{-1}) at conventional (CT-R) stands and those (10.63-10.78 t ha^{-1}) at (CT+R) stands. Soil health also significantly improved at (ZT + R) stands accounting for higher soil porosity (39.45%), pH (7.64), electrical conductivity (0.370 dS m^{-1}), hydraulic conductivity (10.56 mm h^{-1}), soil organic carbon (0.458%), and N, P and K contents (272.5, 18.36 and 254.8 kg ha^{-1}) than at conventional (CT -R) stands.

Therefore, the study could develop a viable cutting-edge agro-technology fostering sustainable maize-wheat production in a system perspective mode. Nonetheless, the stewardship of zero tillage along with stubble residues could also be envisaged for the mitigation of soil sickness, too.

Introduction

Two major cereals, wheat (*Triticum aestivum* L. Emond fiori and Paol) and maize (*Zea mays*, L.) constitute the predominant system of crop rotation providing the platform for significant contribution to the global food basket [1]. Wheat production in India during 2023/24 was 114 M T ranking top 10 States as UP (34 MT), MP (22 MT), Punjab (14.8 MT), Haryana (10.5 MT), Rajasthan (9.5 MT), Bihar (6.2 MT), Gujarat (3.33 MT), Maharastra (2.4 MT), Uttarakhand (0.8 MT), and West Bengal (0.6 MT). Globally, out of total wheat production (785 MT) during 2023/24, China produced the highest (136.6 MT) followed by E Union (134.2 MT), India (114 MT), Russia (91.5 MT), the US (49.31 MT), Canada (31.95 MT), Pakistan (28.2 MT), Australia (26 MT), Ukraine (23 MT), and Turkey (21 MT). While maize production in India during 2023/24 was 34.6 MT with the highest contribution by State Karnataka (5.9 MT) and MP (5.9 MT) followed by Maharastra (4.15 MT), UP (2.8 MT), Bihar (2.4 MT), Telangana (2.1 MT), Gujarat (1.73 MT), Tamilnadu (1.04 MT), and Rajasthan (1.04 MT). Globally, out of total maize production (1170 MT), the US contributed the highest production (382 MT) followed by China (277 MT), Brazil (129 MT), E Union (59.7 MT), Argentina (55 MT), India (34.6 MT), Ukraine (28 MT), Mexico (27.4 MT), S Africa (16.8 MT), and Canada (15.3 MT).

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Most often, expediting sequential cropping patterns may compel farmers to adopt frequent farm operations using heavy farm implements. The situation could further be aggravated following the practice of burning crop stubble residues indiscriminately, which concerns ecosystem issues in India and also most parts of developing countries [2]. However, what farmers are not aware of is inevitable nutrient depletion along with *en mass* destruction of beneficial micro-flora and fauna in addition to the alarming contribution of the C- footprint to the Global Warming Potential (GWP). Therefore, soil degradation, nutrient depletion, and declining groundwater table emerge as the most challenging issues for stagnant crop production [3]. This paramount issue may call for a paradigm shift to conservation agriculture (CA) from conventional agriculture in a global perspective.

Even though, paradoxical views on the *pros and cons* of exploring CA could not accentuate the successful adoption of this technology. Its definite benefits visualizing perceptible improvement in soil health was proclaimed by one School promoting sustainable crop production [4]; while, substantial contradiction could also constitute controversial views defying their notable contribution to soil health [5]. It is evident that likely investigations across diverse soil and agro-climatic situations still remained inconclusive; yet to deliver a vibrant agro-technology becoming imperative while striving for a sustainable climate resilient wheat-maize production system.

A pragmatic understanding of CA protocol addressing conventional tillage *vis-a-vis* no-tillage and retaining crop stubble residues *vis-a-vis* burning crop stubble residues may insist upon the paramount thrust of generating cognitive information attesting either of the school's propaganda for a technology breakthrough developing a viable climate smart agro-technology, strategically feasible among a diverse array of agro-techniques under the aegis of 'CA'.

Thus, critical analyses on consequential influences of different tillage management along with stubble management were conducted in the maize-wheat system during 2019-2022 that intended to generate tangible information in compliance with the 'State of Art' of CA.

Materials and methods

Location of the experiment

The field experiment was conducted for three years consecutively in 2019-20, 2020-21, and 2021-2022 growing wheat in the dry (November - March) season followed by maize in the wet (June - October) season at the research farm of the Indian Agricultural Research Institute, New Delhi, India. Initial analyses of experimental soil estimated low in SOC (0.34%) and N (256.4 kg ha^{-1}), and medium in available P (17.8 kg ha^{-1}) and K (245.6 kg ha^{-1}). Soil was sandy loam analysing 37.98% porosity {1.60 mg m^{-3} bulk density (BD) and 2.58 mg m^{-3} particle density (PD)}, 10.25 m h^{-1} hydraulic conductivity (HC) and 0.36 dS m^{-1} electrical conductivity (EC) with near neutral soil reaction (pH 7.85).

Details of methodologies

Crop stands with zero tillage (ZT) and minimal tillage (MT) were compared with conventional tillage (CT) in compliance with crop residue management, *viz.*, retention of crop stubble residues (R) (CT+R, ZT+R, and MT+R) and burning of crop stubbles i*n situ* (CT-R, ZT-R, and MT-R). Individual dimension of each plot was maintained with their initial demarcation throughout entire experimental periods of three years.

To maintain ZT situations ensured unploughed/untilled soil, where sowing was accomplished with a zero-tilled seed drill; seeds in MT situation were sown within the narrow furrow strips opened at inter-row spaces in untilled soil after previous crops; while CT included usual farm cultivation practices.

Sowing wheat, variety HD 2967 was accomplished with a mechanized seed drill at 22.5 X 15 cm (row X plant) spacing with 25 kg ha^{-1} seed rate and maize, variety PMH 5 A at 30 X 15 cm (row X plant) spacing with 50 kg ha^{-1} seed rate. Recommended doses of fertilizers, i.e., 150 kg N, 80 kg P_2O_5, and 60 kg K_2O ha^{-1} for maize and 150 kg N, 60 kg P_2O_5, and 40 kg K_2O ha^{-1} for wheat were applied as per schedules. As regards residue management treatments, after the harvest of the previous crop, retention of stubble residues was ensured by chopping and uniformly spreading over the plots at 4 t ha^{-1}; while crop stubble resides were burnt *in situ* within the plots conforming the nature of the another treatment.

Soil and plant data collection and analyses

Initial soil samples were collected from an active root zone depth of 15 cm before commencing the field operations and also at the end of 3 years study period for analysing soil physico-chemical parameters. Physical parameters namely, pH, Bulk Density (BD), Particle Density (PD), Hydraulic Conductivity (HC), and Electrical Conductivity (EC); and chemical parameters namely, Soil Organic Carbon (SOC), available Nitrogen (N), Phosphorus (P) and potassium (K) were estimated following standard laboratory procedures as mentioned in Table 1. Crop growth and yield parameters were analysed every year. In the 3rd year, the Available Soil Moisture (ASM) pattern was determined gravimetrically by collecting soil samples from a depth of 15 cm at 10-day intervals across the crop growth from the sowing to the harvesting stage. Root parameters namely root mass and volume were also studied in the 3rd year interpreting sustainable impacts of tillage and crop residue on root growth and development. Root samples were collected at 70 days of growth avoiding denaturation of active root mass.

System productivity of the entire cropping pattern was determined in terms of wheat equivalent grain yields converting maize grain yields taking into account their minimum support prices in the experimental year as declared by the Government of India.

Statistical design and data analyses

To study soil physical and nutritional heterogeneity status uniformly for a smaller number of treatment combinations, three tillage, and two stubble management treatments were randomized in a 'Complete Block Design' with three replications. All data on soil status, plant growth, and available

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soil moisture were subjected to standard Analysis of Variance (ANOVA) using standard statistical procedures. For deriving a logical comparative inference, the treatment differences were compared at a 5% level of significance ($p < 0.05$).

Results

Soil physical properties

Analysing ANOVA for soil physical parameters showed soil BD (1.55 mg m^{-3}) and PD (2.56 mg m^{-3}) derived maximum soil porosity (39.45%) at (ZT+R) stands, which were statistically significant at 5% probability and higher than those (1.66 and 2.65 mg m^{-3}, and 37.35%) at conventional (CT-R) stands as compared with initial status (1.62 and 2.60 mg m^{-3}, and 37.69%) (Figure 1a). While, soil porosity, BD and PD (39.16% and, 1.60 and 2.63 mg m^{-3}) at (MT+R) stands were also statistically significant at 5% probability and higher than those (37.5% and, 1.65 and 2.64 mg m^{-3}) at (CT+R) stands. On the other hand, burning crop residues marginally improved BD (1.58 mg m^{-3}) and PD (2.58 mg m^{-3}) resulting nominal 38.75% increase in soil porosity at (ZT-R) stands; which were although significantly higher than those (38.49% porosity and, 1.63 and 2.65 mg m^{-3}) at (MT-R) stands.

Table 1: Soil parameters analysed and the respective methodology in wheat-maize cultivation during 2019-22.

S. No	Particular	Method employed	Reference
I	Physical Properties		
	1. Bulk density (g cm^{-3})	Core sampler method	Veihmeyer and Hendrickson (1948)
	Particle density (g cm^{-3})	Pycnometer method	
II	Chemical properties		
	pH (1:2.5 soil: water ratio)	Potentiometric method	Jackson, (1973)
	EC (dSm^{-1}) (1:2 soil: water ratio)	EC meter method	Richards (1954)
	Hydraulic Conductivity (mm h^{-1})	Tension infiltrometer method	
	Organic carbon (%)	Walkley and Black method	Jackson, (1973)
	Available N (kg ha^{-1})	Alkaline permanganate method	Subbiah and Asija, (1956)
	Available P (kg ha^{-1})	Olsen's method	Olsen, et al.(1954)
	Available K (kg ha^{-1})	Flame photometer method	Jackson, (1973)

However, soil reaction was barely changed across crop stands (Table 2). Thus, (ZT+R) stands compared with the initial pH (7.78) recorded pH (7.64) comparable with that (7.84) at conventional (CT-R) stands and also those of 7.68, 7.76,7.79 and 7.73 at (MT + R), (ZT-R), (MT-R) and (CT+R) stands respectively.

Similarly, Electrical conductivity (EC) remained mostly unchanged, accounting maximum increase of 0.370 dS m^{-1} at (ZT + R) stands followed by 0.366 dS m^{-1} at (MT + R) and 0.365 dS m^{-1} at (CT + R) stands compared with the initial EC of 0.360 dS m^{-1} (Table 2). Consequences of stubble residue burning also rendered no significant changes at (ZT-R: 0.366 dS m^{-1}), (MT-R: 0.363 dS m^{-1}) and (CT-R: 0.360 dS m^{-1}) stands.

However, compared with the initial HC of 10.06 mm h^{-1}, a maximum of 10.56 mm h^{-1} was at (ZT + R) stands followed by 10.31 mm h^{-1} at (MT + R), significantly higher than conventional (CT-R: 10.0 mm h^{-1}) stands (Table 1). While other stands showed comparable HC accounting 10.22, 10.18, and 10.12 mm h^{-1} at (ZT- R), (MT-R), and (CT +R) stands respectively (Table 2).

Soil organic carbon (SOC) content was also influenced significantly accounting maximum of 0.458% at (ZT + R) stands followed by 0.452% at (MT + R) stands, higher than that (0.446%) at conventional (CT - R) stands as compared with the initial status (0.445%) (Table 1). It remained comparable at other stands accounting for 0.450%, 0.448%, and 0.449% at (ZT - R), (MT - R) and (CT + R) stands, respectively.

Soil chemical properties

Zero tillage also promoted accumulation of soil nitrogen, phosphorus and potassium content, especially with stubble residue retention as compared with their initial contents (255.5 kg N ha^{-1}, 17.8 kg P ha^{-1} and 244.6 kg K ha^{-1}) (Figure 1b). Thus, (ZT+R) stands recorded maximum soil residual nitrogen (272.6 kg N ha^{-1}), phosphorus (18.36 kg P ha^{-1}) and potassium (254.8 kg K ha-1) followed by those (268.4 kg N ha^{-1},18.2 kg P ha^{-1} and 252.2 kg K ha^{-1}) at (MT+R) stands, which were statistically significant at 5% probability and higher than those (248.3 kg N ha^{-1}, 17.2 kg P ha^{-1} and 242.3 kg K ha^{-1}) at conventional (CT-R) stands, and even those (260.35 kg N ha^{-1},18.0 kg P ha^{-1} and

Table 2: Effect of tillage and crop residues management on post- harvest soil physical parameters in wheat-maize cultivation during 2019-22.

Treatments	pH		Electrical Conductivity, dS m^{-1}		Hydraulic conductivity, mm h^{-1}		Soil organic carbon (%)	
	Final estimation/% variation (Initially 7.78)		Final estimation /% variation (Initial 0.358 dS m^{-1})		Final estimation /% variation (Initial 10.06 mm h^{-1})		Final estimation /% variation (Initial 0.445%)	
CT - R	7.84	+0.51	0.360	+0.56	10.0	-1.59	0.446	+ 0.22
ZT -R	7.76	-0.26	0.366	+2.23	10.22	+4.37	0.450	+1.12
MT -R	7.79	+0.13	0.363	+1.40	10.18	+1.19	0.448	+0.67
CT + R	7.73	-0.64	0.365	+1.95	10.12	+1.09	0.449	+0.90
ZT + R	7.64	-1.80	0.370	+3.35	10.56	+4.97	0.458	+2.92
MT + R	7.68	-1.28	0.366	+2.23	10.31	+ 2.48	0.452	+1.57
$SE_{m\pm}$	0.07		0.06		0.08		0.0009	
CD, 5%	NS		NS		0.26		0.003	

CT: Conventional Tillage; ZT: Zero Tillage; MT:Minimum Tillage; "-R": Burning of crop residues; "+R": Retention of crop residues

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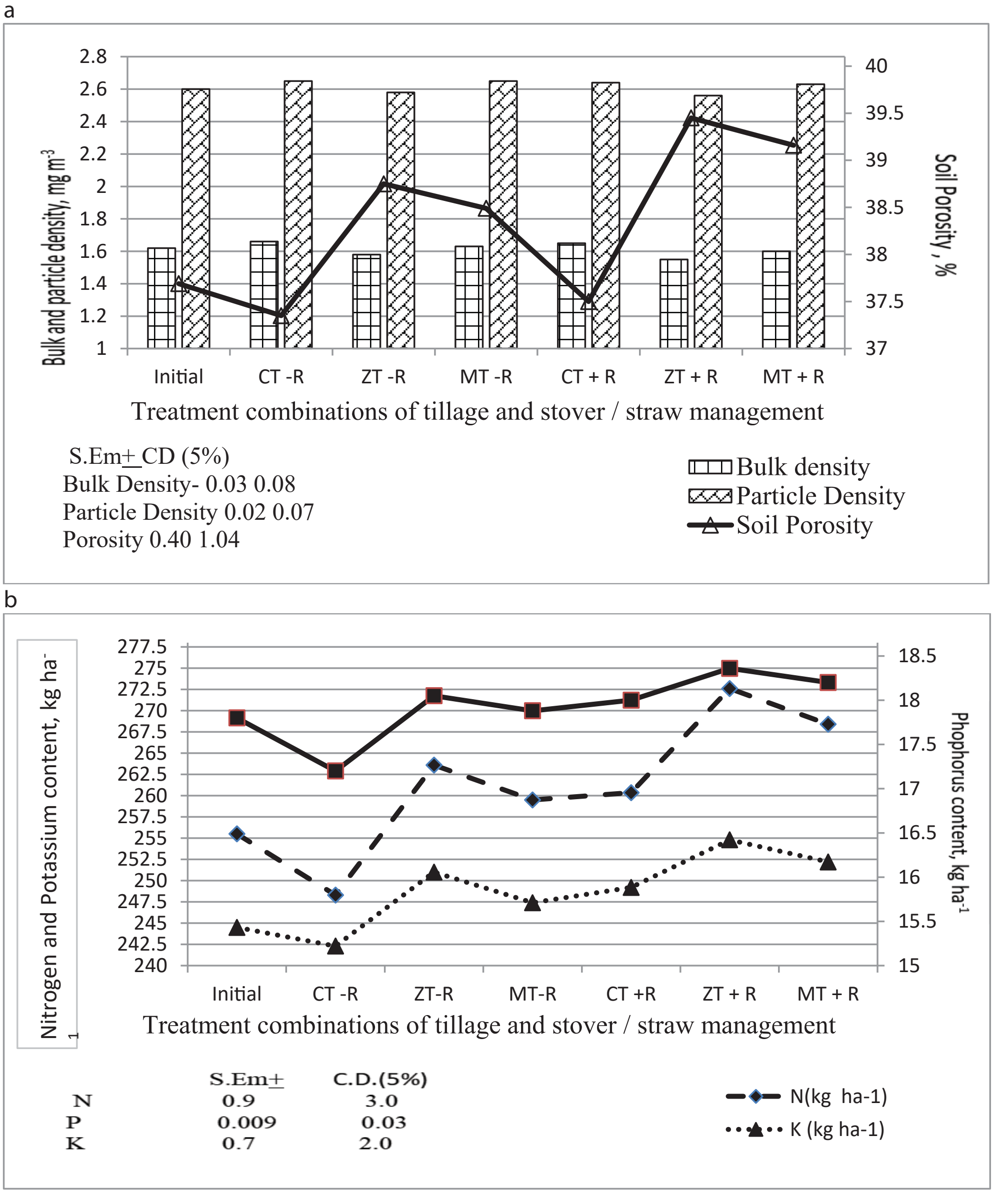

Figure 1a,b: Influences of different tillage and stubble residue management on soil physical (porosity, bulk density and particle density) and Chemical properties (residual soil nitrogen, phosphorus and potassium contents) in wheat-maize cultivation during 2019-2022. . CT: Conventional Tillage; ZT: Zero Tillage; MT: Minimum Tillage; "-R": Burning of stubble residues; "+R": Retention of stubble residues.

249.2 kg K ha^{-1}) at (CT+R) stands. In contrast, stubble burning marginally increased soil N, P, and K contents (263.6 kg N ha^{-1},18.05 kg P ha^{-1}, and 251.0 kg K ha^{-1}) at (ZT-R) stands, which were although, significantly higher than those (N -259.5 kg ha^{-1}, P-17.88 kg ha^{-1} and K 247.4 kg ha^{-1}) at (MT-R) stands, respectively.

Available soil moisture pattern during crop growth

Overall Available Soil Moisture (ASM) in wheat and maize remained around 10% initially; while it started declining towards maturity after culminating during 60 to 70 days of germination (Figure 2a,b). Results showed that (ZT+R) stands facilitated maximum ASM (11.2 to 13.4% in wheat and 11 to 12.4% in maize) across the growth stages than those (10.25 to 11.35% and 9.6 to10.35%) at the conventional (CT -R) stands. While ASM (11.0 to 13.1% and 10.65 to 12.1% respectively) at (MT + R) stands was higher than those (10.75 to 12.54% and 10 to 11.54%) at (CT +R) stands. On the other hand, burning crop stubble declined ASM across tillage management, accounting for relatively lower ASM (10.95 to 12.65%) at (ZT-R) followed by those (10.1 to 12.1%) at (MT-R) stands.

Root architecture

Root mass density was significantly higher in wheat (14.5 mg cm^{-3}) and in maize (19.45 mg cm^{-3}), and volume density in wheat (6.7 x 10^{-3} cm^3 cm $^{-3}$) and in maize (10.5 x 10^{-3} cm^3 cm $^{-3}$) at (ZT + R) stands respectively than those (13.5 and 18.5 mg cm^{-3}, and 5.5 and 9.0 x 10^{-3} cm^3 cm $^{-3}$ respectively) at (CT +R) stands and also those (14.0 and 19.25 mg cm^{-3}, and 6.45 and 9.9 x 10^{-3} cm^3 cm^{-3} respectively) at (MT + R) stands(Figure 3a,b).

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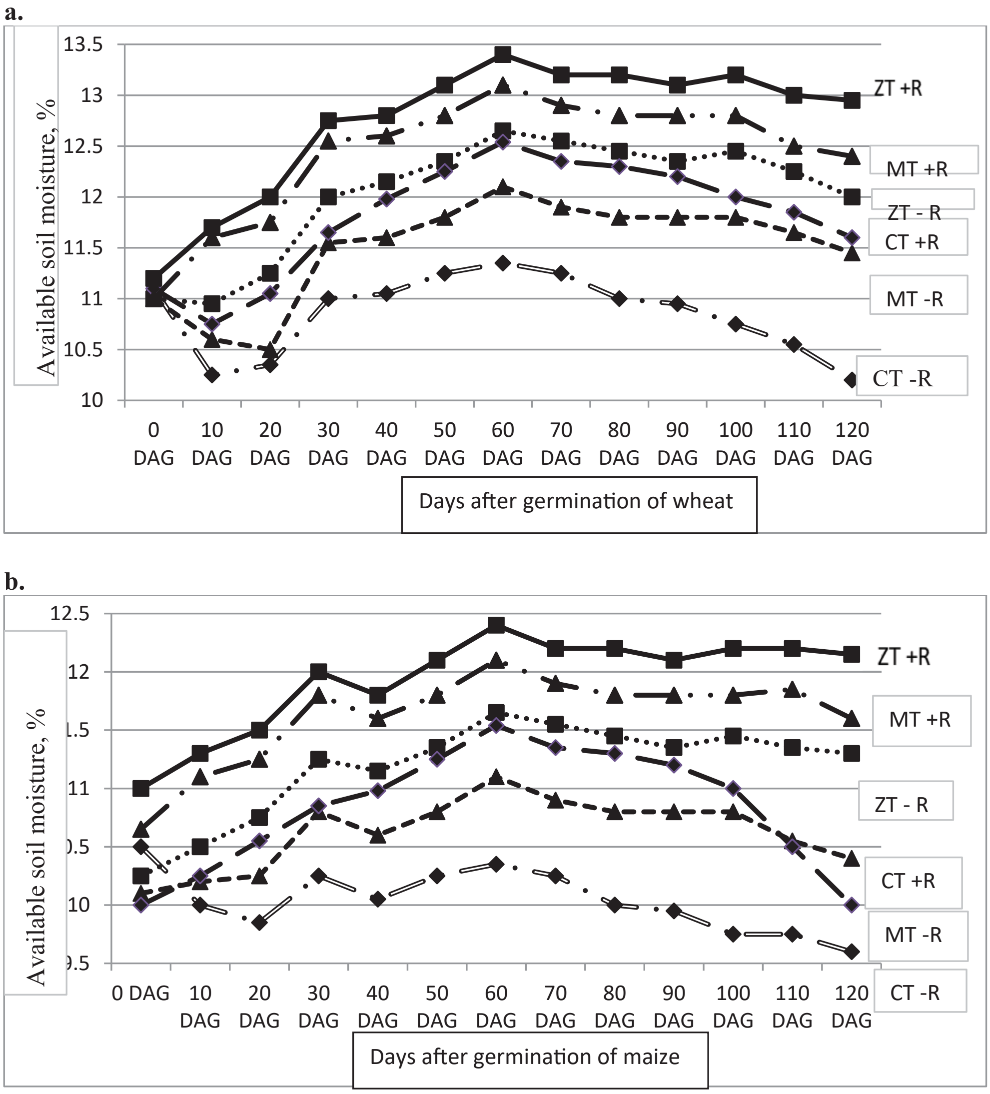

Figure 2a,b: Available soil moisture pattern across crop growth stages in wheat and maize cultivation in 2019- 2022. . CT: Conventional Tillage; ZT: Zero Tillage; MT: Minimum Tillage; "-R": Burning of stubble residues; "+R": Retention of stubble residues.

In contrast, burning crop residues inhibited root growth and development, pronounced more at conventional management accounting for lesser root mass (12.0 and 17.2 mg cm^{-3}) and root volume (5.0 and 8.85 x 10^{-3} $cm^3 cm^{-3}$ respectively) in wheat and maize at (CT-R) stands than those (12.5 and 17.55 mg cm^{-3}, and 9.5 x 10^{-3} $cm^3 cm^{-3}$) respectively at (ZT-R) stands and also those (12.3 and 17.50 mg cm^{-3}, and 6.0 and 9.20 x 10^{-3} $cm^3 cm^{-3}$) respectively at (MT-R) stands.

Grain yields

In cognizance with persistent growth and developments, both the crops at (ZT +R) stands achieved maximum grain yields (wheat: 5.64, 5.69 and 5.78 t ha^{-1}) and those (maize: 6.52, 6.60 and 6.74 t ha^{-1}) progressively during 1st, 2nd and 3rd year, which was statistically significant at 5% probability and higher than those (wheat: 5.25, 5.24 and 5.25 t ha^{-1}) and those (maize: 5.76, 5.75 and 5.76 t ha^{-1}) at conventional stands (CT-R) (Table 3). While, (MT +R) stands produced which was statistically significant at 5% probability and higher than grain yields (wheat: 5.59, 5.63 and 5.70 t ha^{-1}) and those (maize: 6.29, 6.32 and 6.40 t ha^{-1}) than those (wheat: 5.30, 5.31 and 5.33 t ha^{-1}) and those (maize: 5.83,5.85 and 5.88 t ha^{-1}) at (CT +R) stands respectively.

On the other hand, consequences of burning residues at (ZT- R) stands declined grain yields to 5.56, 5.58, and 5.64 t ha^{-1} in wheat, and 6.43, 6.48 and 6.60 t ha^{-1} in maize during corresponding year, which were although statistically significant at 5% probability and higher than those (wheat: 5.53,5.55 and 5.57 t ha^{-1}) and those (maize: 6.22,6.23 and 6.25 t ha^{-1}) at (MT-R) stands.

Pooled grain yields over three years of study also showed maximum grain yields (wheat: 5.70 t ha^{-1} and maize: 6.62 t ha^{-1}) at (ZT + R) stands followed by those (5.64 t ha^{-1} and 6.34 t ha^{-1}) at (MT+R), which were statistically significant at 5% probability and higher than those (5.25 and 5.76 t ha^{-1}) at conventional stands (CT-R) and even at (CT+R) stands (5.31 and 5.85 t ha^{-1}).

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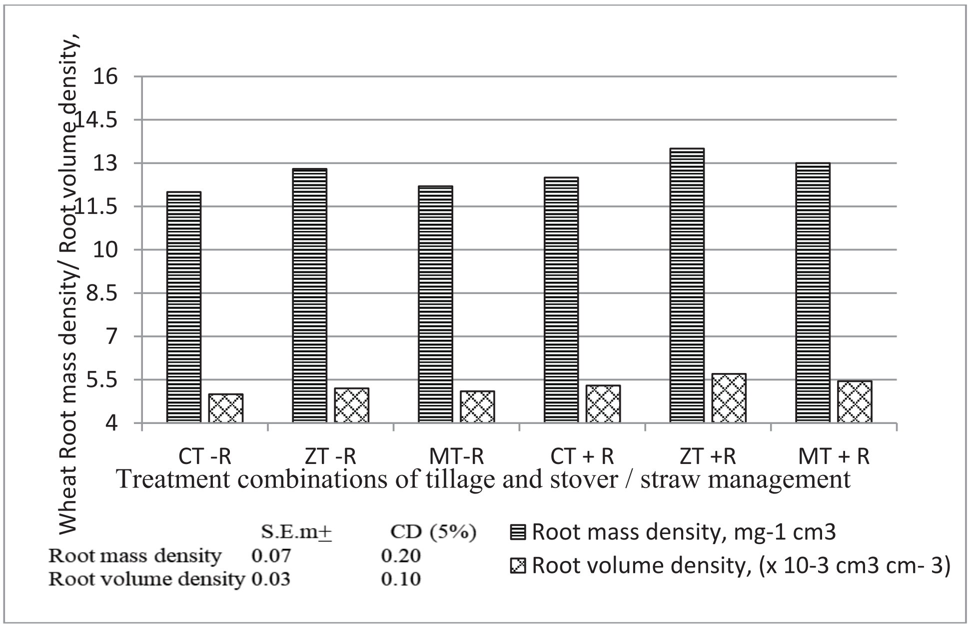

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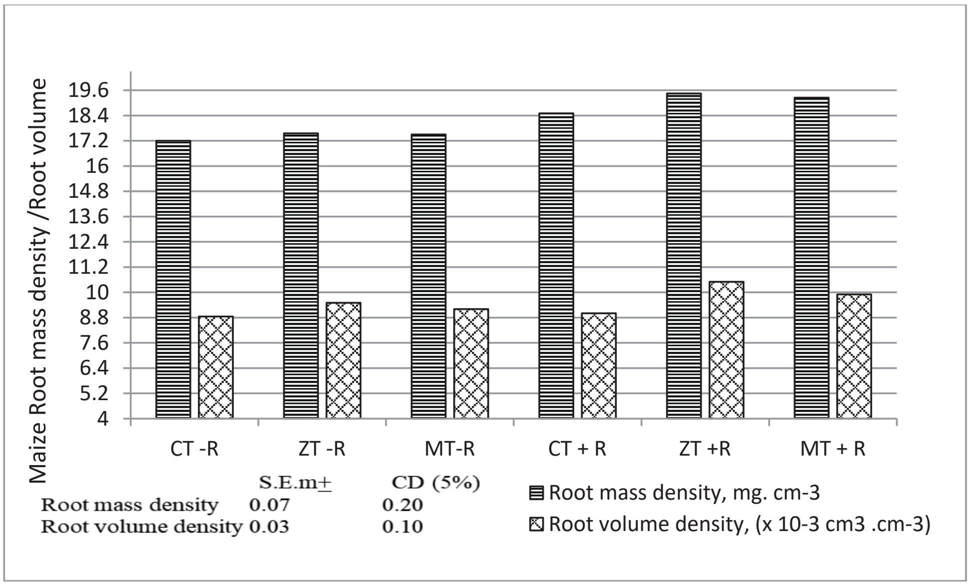

Figure 3a,b: Influences of different tillage and stubble residue management on root architecture (volume and mass density) in wheat and maize cultivation during 2019-2022. . CT: Conventional Tillage; ZT: Zero Tillage; MT: Minimum Tillage; "-R": Burning of stubble residues; "+R": Retention of stubble residues.

System productivity

System productivity in terms of 'wheat equivalent yields' was maximum at (ZT + R stands accounting for 11.60, 11.87, and 12.0 t ha^{-1} followed by those (11.44, 11.65 and 11.76 t ha^{-1}) at (ZT – R) stands and those (11.34, 11.55 and 11.64 t ha^{-1}) at (MT + R) stands in the successive year, which was statistically significant at 5% probability and higher than those (10.52, 10.63 and 10.59 t ha^{-1}) at conventional stands (CT – R) and even those (10.63 t ha^{-1}, 10.75 t ha^{-1} and 10.78 t ha^{-1}) at (CT + R) stands (Figure 4).

Deriving pooled system productivity over the years of study revealed maximum of 11.82 t ha^{-1} at (ZT+R) stands, followed by those of 11.61, 11.52 and 11.32 t ha^{-1} at (ZT – R), (MT + R) and (MT -R) stands respectively, which were statistically significant at 5% probability and higher than that (10.58 t ha^{-1}) at conventional stands (CT – R) and also that (10.72 t ha^{-1}) at (CT + R) stands (Figure 4).

While analyzing individual impacts of tillage could ascertain overall higher system productivity (11.71 t ha^{-1}) at ZT stands across residue management *par se* followed by MT (11.41 t ha^{-1}) than at CT (10.65 t ha^{-1}) stands. Similarly, retention of stubble residue (+ R) could promote higher grain yield (11.35 t ha^{-1}) across the tillage management than that (11.17 t ha^{-1}) at the stands affected by burning stubble (– R).

Table 3: Effect of tillage and crop residue management on grain yields (t h-1) of wheat – maize during 2019-22.

Period	1st year		2nd year		3rd year		Pooled	
Crops	Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize
CT-R	5.25	5.76	5.24	5.75	5.25	5.76	5.25	5.76
ZT-R	5.56	6.43	5.58	6.48	5.64	6.60	5.59	6.50
MT-R	5.53	6.22	5.55	6.23	5.57	6.25	5.55	6.23
CT+R	5.30	5.83	5.31	5.85	5.33	5.88	5.31 (>1.14%)$	5.85 (>1.62%)
ZT+R	5.64	6.52	5.69	6.60	5.78	6.74	5.70 (>1.97%)	6.62 (>1.85%)
MT+R	5.59	6.29	5.63	6.32	5.70	6.40	5.64 (> 1.62%)	6.34 (>1.76%)
$SE_{m\pm}$	0.014	0.07	0.017	0.08	0.018	0.09	0.017	0.085
CD, 5%	0.04	0.22	0.05	0.24	0.05	0.26	0.05	0.25

$- compared with corresponding residues burning, CT: Conventional Tillage; ZT: Zero Tillage; MT: Minimum Tillage; "-R": Burning of crop residues, "+R": Retention of crop residues

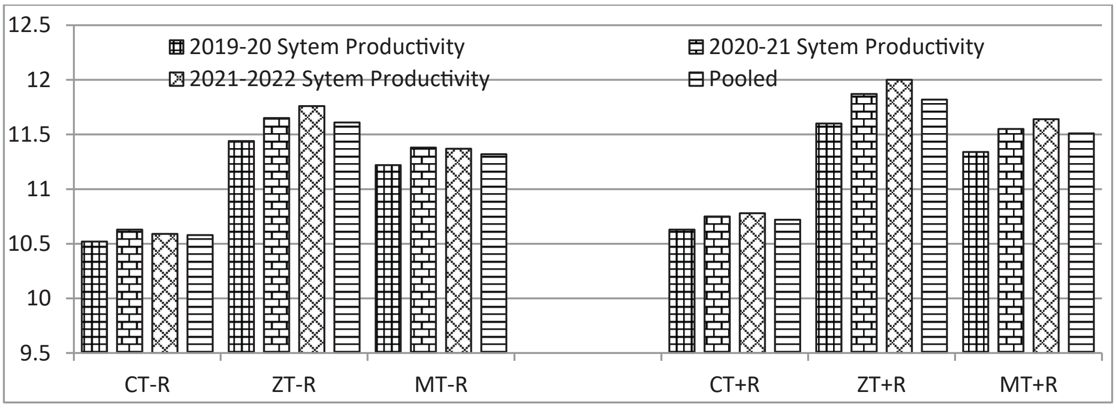

Figure 4: Influences of different tillage and crop stubble residue management on system productivity in maize-wheat cropping pattern during 2019-20, 2020-21 and 2021-22. CT: Conventional Tillage; ZT: Zero Tillage; MT: Minimum Tillage; "-R": Burning of stubble residues; "+R": Retention of stubble residues. Minimum support price of wheat were INR 1925.0 kg-1, 1975.0 kg-1 and 2015 kg-1, and INR 1760.0 kg-1, 1850.0 kg-1 and 1870.0 kg-1 during 2019-20, 2020-21 and 2021-22.

Discussion

Three years' intensive study on the wheat-maize system perspective could crystalize a prospective agro-technology against the backdrop of the eventuality of traditional farming that becomes an alarming issue threatening *en mass* endeavour while striving to achieve the future commitment to sustainable food, nutrition, and environmental security.

Soil physical properties

Perceptible improvement in soil health attributed to multi-faceted dimensions in structural, nutritional, and micro-biological development occurred consequent upon zero tillage supplemented with stubble residues. This could be attributed to the substantial formation and stabilization of soil aggregates concurrence upon the accumulation of organic matter as a binding agent by virtue of crop residue retention [6]. While the eventuality of stubble burning ended with reverse impacts on soil sickness envisaging a drastic decline in potential soil and crop productivity.

Compared with the initial status, the soil porosity at (ZT+R) stands significantly increased to 4.67% followed by (MT+R) stands with a 3.90% increase, attributed to the lesser BD and PD. In contrast, relatively higher BD and PD marginally decreased 0.50% porosity in (CT+R) stands. Burning crop stubble resulted in relatively less soil porosity improvement (2.81% and 2.12%) despite reducing tillage in (ZT-R) and (MT-R) stands. Corroborating with previous reports, the study confirmed that microbial decomposition of crop residues to polysaccharides and excreta/gum secretion from microorganisms could act as soil particle binding agents resulting in improvement in soil aggregation and porosity [7]. Besides, retention of stubble residue could also promote numerous biotic activities within the soil matrix substantiating soil aggregates improvement.

The implication of short-term management practices could barely bring about any radical changes in soil reaction, that too within a span of only 3 years as they are inherently less responsive to any short-term soil manipulation [8]. Very pertinently, pH was not much influenced accounting for a meagre reduction of 1.80% at (ZT +R) stands, followed by 1.28% and 0.64% reductions in (MT+R) and (CT+R) stands respectively. While stubble burning increased soil pH (0.51% and 0.13) both at (CT-R) and (MT-R) stands respectively; however, with an exception of 0.26% decline at (ZT-R) stands, instead.

A similar trend also happened in Electrical Conductivity (EC) causing nominal changes with a maximum increase of

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3.35% in (ZT + R) stands followed by (2.23%) in (MT + R) stands compared with the initial EC. While, consequences of stubble burning also increased EC accounting for 2.23%, 1.40%, and 0.56% in (ZT -R), (MT-R), and (CT-R) stands respectively.

Hydraulic Conductivity (HC) also varied marginally increasing 4.97% at (ZT + R) stands followed by 2.48% and 1.59% increase at (MT + R) and (ZT- R) stands respectively compared with the initial HC. EC at (MT - R) stands increased by 1.19% followed by 0.60% at (CT + R) stands, while EC recorded a 0.060% decrease at conventional (CT - R) stands. The improvement in HC might be attributed to the addition of crop residues promoting soil aggregates, better root penetration, and continuous channels formed by decaying root mass facilitating easy and uninterrupted soil water movement. The lower HC in the event of stubble burning might be due to soil compaction restricting soil water flow uninterruptedly.

Cumulative impacts of residue retention over the years might be attributed to supplementary preservation of plant biomass that could simultaneously inhibit mineralization of SOM accelerating C-sequestration in the system [8]. Thus, comparing with initial status, Soil Organic Carbon (SOC) increased by 2.92% and 1.57% while reducing tillage was supplemented with stubble residues retention at (ZT + R) and (MT + R) stands compared with 0.22% increase at conventional tillage (CT - R) stands, followed by 0.90% at (CT +R) stands. Burning stubble depleted SOC accumulation despite minimizing tillage accounting for only 1.12% and 0.67% increase at (ZT-R) and (MT-R) stands respectively. Evidently, C- Sequestration, another paradigm development in soil health was thus accentuated by virtue of crop stubble residue retention having been endowed with the restoration of total Soil Organic Matter content (SOM) as compared with burning of crop stubbles. Thus, in view of the beneficial impacts of SOM on soil physico-chemical and biological properties, the study may advocate either replenishment of C inputs or diminishing C losses aiming at avoiding phenomenal adverse impacts that could often deteriorate soil health at the cost of simultaneous intensive tillage operations.

Soil chemical properties

Changes in soil chemical properties attributed primarily to residual soil N, P, and K contents were quite substantial due to varying soil tillage and crop stubble residue management. Wang, et al. [9] also expressed similar views while explaining the merits of zero tillage with crop stubble residues balancing the carbon-nutrient ratios for sustainable soil health. Besides, substantial nutrient loss was also reported to have been incurred on stubble burning accounting for around 90% depletion of N and S, and 15-20% of P and K in rice [10]. The current study could establish that minimal soil disturbances along with crop residue retention replenished soil N, P, and K content, pronouncing 6.7%, 3.1% and 4.2% increase at (ZT + R) stands as compared with initial soil NPK status respectively, which were significantly higher than those (1.9% N, 1.1% P and 1.9% K) at (CT+R) stands and also those (5.0% N, 2.2% P and 3.1% K) at (MT+R) stands. In contrast, stubble burning caused substantial depletion by 2.8%,3.4% and 0.9% in residual soil N, P, and K contents in (CT-R) stands as compared with the increase of 3.2%,1.4% and 2.7% in (ZT - R) stands and also by 1.6%,0.5% and 1.2% in (MT-R) stands. Evidently, zero tillage could maintain the ambient soil micro-environment energizing microbial activities to mobilize decomposition and subsequent mineralization of SOM, supplemented with crop residue retention. Nonetheless, Yaduraju and Mishra [11] expressed a different view that undisturbed soil conditions at zero tillage could reduce weed pressure restricting incidental nutrient mining. In addition, relatively soft and moist surface soil could expedite early seed emergence getting them imbibed with considerable weed-smothering ability following an immediate 'head start' of wheat seedlings over weeds.

Available Soil Moisture (ASM)

Critical analyses showed the potentiality of (ZT+R) stands reducing surface soil encrustation and increasing water infiltration by impeding surface runoff losses sustaining ASM across crop growth [12]. This stands enhanced soil moisture retention across the stands pronouncing a total of 165.6% in wheat and 155.1% in maize respectively followed by 161.6% in wheat and 151.0% in maize at (MT + R) stands, and 153.6% (wheat) and 140.8% (maize) at (CT +R) stands respectively. On the other hand, burning stubble depleted total ASM to 149.5% (wheat) and 138.1% (maize) at (MT-R) stands, and 141.0% (wheat) and 130.5% (maize) at (CT-R) stands; although, (ZT-R) witnessed relatively higher total ASM (145.3% and 156.4%), instead. Again, overall mean ASM across crop growths prevailed higher with stubble retention at (ZT +R) pronouncing 11.9% (maize) and 12.8% (wheat) followed by 11.6% (maize) and 12.5% (wheat) at (MT+R) stands, and 10.8% (maize) and 11.8% (wheat) 11.8% (wheat) at (CT+R) stands respectively. While, ASM at stands affected with stubble burning was comparatively less accounting for 11.2% (maize) and 12.0% (wheat) at (ZT -R) stand, 10.6% (maize) and 11.5% (wheat) at (MT -R) stands, and 10.0% (maize) 10.8% (wheat) at (CT-R) stands. Supporting the current observations, Govaerts, et al. [12] also reported that likely practices of depriving soil with crop residues accentuated crust formation with low soil aggregation resulting in relatively impermeable soil layer by sealing micro-pores, thus infiltration and moisture storage ability of the soil declined substantially.

Root architecture

Undisturbed soil strata with the influence of stubble residues prompted root development substantially, which was attributed to the significant improvement in root mass and volume. Meena and Behera [13] also reported an increase of 12% root mass and 14% root volume at (ZT + R) stands, followed by those (8.3% and 9%) at (MT +R) stands compared with conventional stands (CT-R), followed by those (4.17% and 6%) at (CT+R) stands The situation became precarious in stands affected with crop stubble burning despite reducing tillage, evidenced at (6.7% and 4%) in (ZT-R) and those (1.7% and 2%) at (MT-R) stands. Intensive tillage could generate multi-avenues accentuating water losses, an eventual consequence of higher soil porosity and surface roughness exposing more surface areas for moisture evaporation losses particularly. Besides, excess water accumulation at the rhizosphere

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immediately after irrigation at CT stands could also cause root stunting due to rapid N-nutrient loss upon leaching and denitrification [14].

Grain yields

Native soil profile having been nourished with crop residues at zero tillage stands created a congenial micro-environment that consistently prompted growth and development of the crops *ceteris paribus* with the other factors across the year of study. Thus, the potentiality of (ZT+R) stands sustained progressively increasing productivity by 7.43, 8.59%, and 10.09% in wheat and 14.76%, 14.78% and 15.01% in maize over the conventional stands (CT- R) across the year, respectively [15]. Even impacts of stubble retention were also pronounced at (MT + R) stands boosting 6.45%, 7.44% and 8.57% grain yields in wheat, and 9.2%,10.2% and 11.1% grain yields in maize, and also 0.95%,1.3% and 1.5% in wheat and 1.21%,1.74% and 2.08% in maize at (CT + R) stands comparing conventional stands (CT-R) stands. On the other hand, the proportionate increase in grain yields at the event of burning stubble at (ZT-R) was 5.90%, 6.48% and 7.42% in wheat and11.63%,12.69% and 14.58% in maize, and also at (MT-R) stands by 5.3%,5.9% and 6.09% in wheat and7.99%,8.35% and 8.50% in maize comparing with conventional tillage stands (CT-R). Thus, the present investigation could logically contradict earlier studies reporting the demerits of crop stubble residue incorporation [5].

System productivity

Subsequently, (ZT + R) stands boosted system productivity by 10.27%, 11.67%, and 13.31% during the 1st, 2nd, and 3rd year respectively over conventional stands (CT - R) with an overall enhancement of 11.72%. System productivity also boosted in (MT+R) stands by 7.79%, 8. 65%, and 9.91%, and also at (CT+R) stands by 1.0%,1.1% and 1.79%. On the other hand, the impact of stubble retention was also visualized achieving 1.81%, 1.68% and 1.32% more system productivity at ZT, MT, and CT stand over their corresponding stands affected with burning stubble.

Soil health

The study confirmed the development of soil health by virtue of sustained impacts of zero tillage management, conspicuously evident across the years. To alleviate soil sickness pronouncing more conducive to plant growth and development was ascertained by virtue of an undisturbed soil environment in addition to preventing SOM depletion. However, eliminating the adversity caused due to consequential soil disturbances with traditional farming would require considerable passage of time to regain optimum soil physico-hydrological environment; while the decomposition-immobilization-mineralization process is also subject to considerable time span following the incorporation of plant biomass [16].

Many factors in cognizance with zero tillage and crop residue management could be attributed while improvement in yield parameters was interpreted for sustainably higher grain yield in wheat and maize in this study. Recycling crop stubble residues certainly returns a substantial quantity of organic matter back into the soil, which could inherit consistent potential in C-sequestration in particular and overall soil health improvement in general. As a consequence, the accumulation of soil nutrients could be accelerated sustaining subsequent availability to promote better crop growth and productivity.

Despite generating quite tangible information, the study has the limitation of addressing some more issues. Thus, information on ‘Argonomics’ while reducing the drudgery of tillage implements, soil microbiological dynamics, and emission of GHG especially oxides of N determining the GWP of these practices need to become the future direction in likely studies .

Conclusion

Therefore, the current study could establish that sustainable improvement in soil health *vis-a-vis* crop growth and vigour should imperatively go ‘hand in hand’ to ascertain ‘CA’ in the right perspective. Thus, improving the soil matrix in compliance with crop residue retention and elimination of soil inversion becomes the most pragmatic cutting-edge strategy in cognizance of sustainable food and environment security. The current study may very emphatically confirm the merits of zero tillage, pronounced more with crop residue retention for conserving soil, water, and nutrients as prime component practices within the gambit of sustainable agriculture. While burning crop residues certainly emerges detrimental not only to the soil health but crop health too. Nonetheless, sequential influences of zero tillage over the years could gear up biomass accumulation for nutrient acquisition compared with conventional tillage management.

Therefore, the following salient inferences could epitomize vibrant agro-technology for the mitigation of soil sickness to foster sustainable wheat and maize production. Firstly, the information generated in the study could warn traditional tillage with heavy farm implements and indiscriminate burning of crop stubbles. Secondly, the stewardship of zero tillage in cognizance of crop residue retention may be advocated from the right perspective. Lastly, such integration should remain instrumental in boosting system productivity in the wheat-maize system, which would be expected to help crop-ecology congregations synchronize the dynamic equilibrium to ensure sustainable food and environment security.

(**Supplementary**)

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