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# Conservation Agriculture protocols alleviating adversity of tillage and burning stubble induced soil physico-chemical anomalies in sustainable wheat production under rice-wheat system

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## ABSTRACT

Conventional tillage and crop stubble burning are usual practices across the rice-wheat cropping system (RWCS) in India. These could aggravate soil sickness, threatening food and environmental safety. Thus, the main aim of this study was to establish improved crop management following the Conservation Agriculture (CA). Accordingly, the objectives to determine prospects of CA protocols (a) zero tillage and (b) retention of crop stubbles were studied in the Indian Agricultural Research Institute, New Delhi from 2022 to 2025. Six treatments - retention of crop stubbles (+ CS) at zero tillage (ZT+ CS), minimum tillage raised bed (RB+ CS) and conventional tillage (CT+ CS) stands were compared with burning crop stubbles (- CS) at corresponding tillage stands (ZT-CS, RB-CS and CT-CS). Results showed higher soil porosity (39.45%), soil organic carbon (SOC) (0.360 %), available soil moisture (12.78%), residual N, P and K (272.6, 18.36 and 254.8 kg ha$^{-1}$) content, root mass density (14.75 mg cm$^{-3}$) and root volume density (6.1 x 10$^{-3}$ cm$^3$ cm$^{-3}$) at (ZT+CS) stands. This stand also recorded higher wheat productivity (5.64-5.94 t ha$^{-1}$) throughout all the years, which was statistically significant than other stands (RB+ CS) and (CT+CS). While grain yields declined to 5.56-5.65 t ha$^{-1}$ at (ZT-CS), 5.53-5.57 t ha$^{-1}$ at (RB-CS), and 5.24-5.25 t ha$^{-1}$ at (CT-CS) stands. Therefore, implications of the study may envisage the stewardship of CA that does not incur additional cost of production. Thus, farmers could be advocated for transitioning from conventional farming to CA-based farming for sustainable wheat production.

**Keywords:** Crop stubble burning, Grain yield, Soil health, Wheat, Zero tillage.

## INTRODUCTION

The rice-wheat cropping system (RWCS) is one of the predominant production systems in Indo Gangetic plains (IGP). This cropping system usually contributes substantially to the national and global food front. Out of total 13.5 million hectares in Asia, around 57% area is spread in south Asian region; while Indo-Gangetic Plains (IGP) accounts for around 85% of these RWCS areas (Dhanda *et al,* 2022).

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Farmers pursuing this RWCS usually confront challenges while preparing land for immediate wheat crop. As removing stubbles of previous *kharif* rice in a short span becomes a formidable issue. So, burning stubbles is the only quick option due to unavailability of any other cost-effective feasible alternatives while intending sequential wheat crop.

What they do not realize the far-reaching detrimental consequences of soil nutrient depletion, global warming, etc. In addition, *en mass* destruction of beneficial micro- flora and fauna was also evidenced that could decline the sustainable system productivity.

In addition, soil tillage with heavy farm implements can further exacerbate the situation. As frequent mechanized farm operations may deteriorate the structural health of soil. Consequently, soil compaction along with nutrient mining appears to become the most vulnerable issues plateauing system productivity. Consequently, destabilizing the production potentiality in crop growing ecology ~~agro-ecological stability~~ may threaten the sustainable food system globally, too.

As a result, challenges to restrict qualitative and quantitative deterioration of farm resources resulting unsustainable crop productivity needs to be addressed following the 'Conservation agriculture' (CA) protocols.

CA could be considered one of the pragmatic approaches to restore, conserve and sustain soil health. In 1998, Food and Agricultural Organization at its first regional CA workshop in Harare, Zimbabwe, explained it as an ecosystem approach with three interlinked principles, *viz.*, minimum soil disturbance, maintaining a permanent soil mulch and crop diversification with the aim of sustainable agriculture (Marongwe, *et al.*, 2012). Globally, CA occupies around 205.4 M ha area, while 3.5 M ha area is under CA in India (Kassam et al, 2022).

Even though, apprehension on substituting conventional practice of tillage and rice stubble management could demotivate adoption of this improved technology in global perspective (Huang et al., 2015; Sayre *et al*., 2007; Jin and Wu,2021). Its cognitive benefits realizing perceptible improvement in soil status was established in one hand; while, substantial contradiction constituted the argument defying their contribution on yield attributing factors in other hand. Therefore, present study analyzes two differing opinions comprising with the paradoxical views of CA protocols to establish whatever beneficial to the RWCS farmers.

Thus, despite recognizing the rationale outlined above, the research gap has emerged for a holistic study across diverse agro-ecological regions. The outcome of which remained inconclusive until now that inspired us to plan the prent experiment. Therefore, it is imperative to develop a viable agro-technology in view of CA while striving for sustainable productivity in the RWCS ~~sustainable climate-smart RWCS,~~ instead.

The pragmatic understanding whether no tillage and crop stubbles retention could replace conventional farm practices may help formulate the current field study. Wherein, useful contribution of the current study could be visualized in right perspective that could be strategically feasible across RWCS aiming the holistic system benefit.

In view of above rational, current study was conducted with two broad objectives; a). to determine advantages of zero tillage management and b). impacts of incorporating rice crop stubbles in comparison with conventional tillage and stubble burning in the wheat crop under the of aegis of RWCS.

## MATERIALS AND METHODS

### Location of the experiment

Field studies were conducted growing wheat (*Triticum aestivum* L. Emond fiori and Paol) consecutively over three dry seasons (2022-23, 2023-24 and 2024-25) following the harvest of preceding wet / *kharif* rice (*Oryza sativa,* L.) at the Indian Agricultural Research Institute, New Delhi. The farm soil belonged to order *Inceptisol* analysing below normal SOC (0.346 %) and N (255.5 kg $ha^{-1}$) content, and medium in available P (17.8 kg $ha^{-1}$) and K (244.5 kg $ha^{-1}$) content. The soil was sandy loam with a bulk density (BD) of 1.62 Mg $m^{-3}$ and a particle density (PD) of 2.60 Mg $m^{-3}$ deriving 37.69% porosity and the soil pH was near neutral at 7.76.

### Details of Treatments

The study compared the effects of three tillage management methods- conventional tillage (CT), zero tillage (ZT) and minimum tillage raised bed (RB)- with two rice stubble management practices: stubble retention (+ CS) and crop stubble burning (- CS).

As a result, six treatment combinations were established- retention of rice stubbles in zero tillage (ZT+ CS), minimum tillage raised bed (RB+ CS) and conventional tillage (CT+ CS) stands, and rice stubble burning at corresponding tillage systems (ZT- CS, RB-CS and CT-CS). The entire treatment set was arranged within permanent field plots, which were maintained over three-year study period, with plot dimensions remaining unchanged throughout.

In this study, ZT was considered as one of the protocols of CA in view of ensuring minimum or no soil disturbances while comparing with detrimental impacts of CT. Crop stubble retention conserving organic matter was considered comparing with harmful effects of conventional practice of their burning. Even destruction of soil microbes on account of high soil temperature may also occur apart from aggravating GHG ($CO_2$) emission, a potential contribution to GWP.

**Details Methodologies**

Stubble residues, after rice harvest, were chopped and spread at 4 t ha$^{-1}$ uniformly over all treatment specific plots; while, rice stubbles were burnt *in situ* within the treatment specific plots. Traditional tillage comprised of deep ploughing at a depth of 50 cm once with the tractor-drawn disc plough followed by two cross harrowing subsequently after a week and immediate levelling with the tractor-drawn rotavator. To maintain ZT situations ensured unploughed / untilled soil, where sowing was accomplished with a zero-tilled seed drill; another treatment, ridge bed (RB) stands were designed mechanically fixing the dimension of 15 cm height and 20 cm width using the 'Bed Planter'; while CT included usual farm tillage practices. CT comprised of both primary tillage for deep ploughing with disc plough to break compacted soil layer followed by secondary tillage with harrows and rotavator for proper soil pulverization, finally. The test variety of wheat was HD 2967, a semi-dwarf (101 cm) variety developed by the Indian Agricultural Research Institute (ICAR-IARI), New Delhi. It is known for its good grain quality with high iron and zinc content. It is suitable for cultivation in the North-Western and North-Eastern Plains Zones of India. It could mature within 130-145 days with a potential grain yield of 4.5-5.5 t/ha.

Wheat was sown at a seed rate of 25 kg ha$^{-1}$ maintaining the spacing of 22.5 X 15 cm (row X plant). To economize the seed requirement at 25 kg ha$^{-1}$ only followed the dibbling method of dropping 2-3 seeds per hill. Thus, a tractor-drawn seed drill was used at the predetermined plant spacing reducing seed rate from the usual seed rate of 100-125 kg ha$^{-1}$ for conventional method.

N, P and K were applied as per recommendation, i.e., 150 kg N, 26.2 kg P and 33.05 kg K ha$^{-1}$ following standard management schedules, i.e., the full dose of P and K, and half the dose of N were applied at sowing: while, remaining half of N was applied at the crown root initiation stage.

**Analyses of plant and soil parameters- its significance**

Significance of soil physical and chemical parameters has profound impact on soil health, which in turn could determine crop growth. Those attributes not only regulate availability of soil nutrients, but physical micro environment for root proliferation, water holding ability, available soil moisture, etc, too. Consequently, determining those parameters while exploring improved soil and crop residue management could interpret the progressive development of soil health from its original status.

Therefore, soil health variation across the treatments and also over the year of study were determined analysing key soil physical and chemical parameters namely, bulk density (BD), particle density (PD), soil organic carbon (SOC), available nitrogen (N), phosphorus (P) and potassium (K) (Quiamco,1993).

Initial soil samples were collected before the field experiment began and again at the end of the study from the active root zone (15 cm depth) as suggested by Fan et al, (2016).

All above soil parameters were estimated following methods as suggested by Quiamco (1993); Bulk Density by Core sampler, Particle Density by Pycnometer method, pH by Potentiometric method, Electrical Conductivity by EC meter, Hydraulic Conductivity by Tension infiltrometer method, Organic Carbon by Walkley and Black method, available nitrogen by alkaline permanganate, available phosphorus by Olsen method and potassium by Flame photometer methods, respectively.

While, soil water content in active root zone was measured gravimetrically during the third year by collecting samples at 10 days interval. Rhizosphere development was assessed in the third by analysing root mass and volume density, which provided insight into the combined effects of tillage and rice stubble on root growth. Root samples were collected at 70 days of growth to avoid loss of active root mass during sample collection.

**Statistical Design and data analyses**

'Randomized Complete Block Design' (RCBD) was followed distributing treatments under three replications for standard analysis of variance (ANOVA) using standard statistical procedure (Gomez and Gomez, 2010). The treatment variations were compared at least significant difference (LSD) tests at 5% level of significance ($P<0.05$).

## RESULTS

**Soil physical and chemical properties**

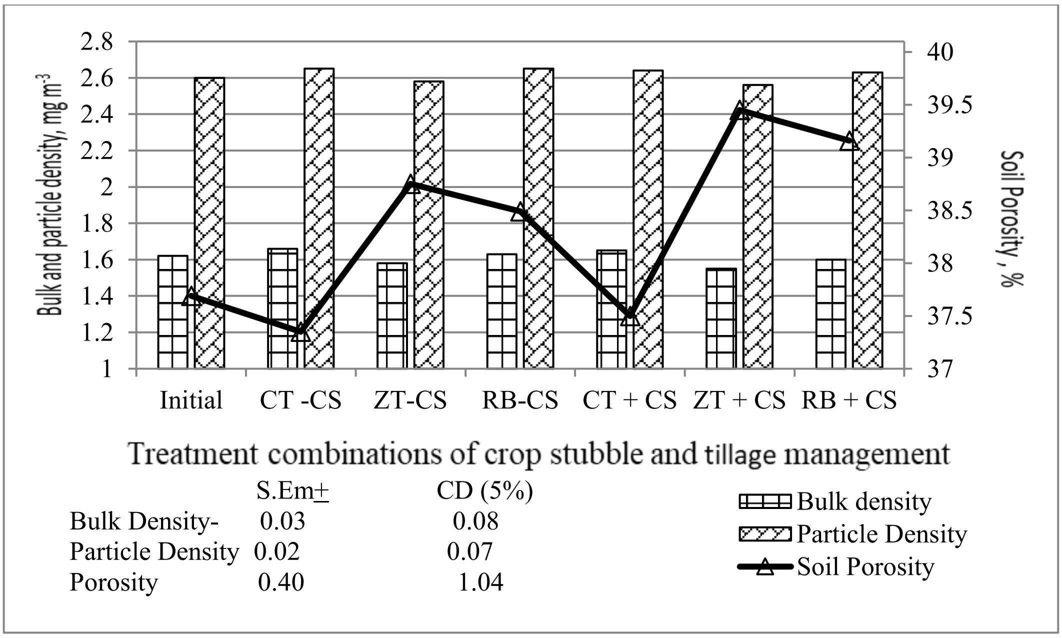
Retention of crop stubble under zero tillage (ZT + CS) significantly increased soil porosity (39.45%), compared to other treatments, which could be attributed to decrease in Bulk density (1.55 mg $m^{-3}$) and Particle density (2.56 mg $m^{-3}$). The relatively lower Porosity in (RB+CS) stands (39.16%) was attributed to higher Bulk density (1.60 mg $m^{-3}$) and Particle density (2.63

mg m$^{-3}$). This was in comparison to the initial values of 37.69% Porosity, 1.62 mg m$^{-3}$ Bulk density and 2.60 mg m$^{-3}$ Particle density (Figure 1).

In contrast, Porosity (37.50%) in (CT+CS) stands marginally improved due to higher both bulk density (1.65 mg m$^{-3}$) and particle density (2.64 mg m$^{-3}$). Similarly, (ZT-CS) stands showed a slight increase in porosity (38.78%), Bulk density (1.58 mg m$^{-3}$) and Particle density (2.58 mg m$^{-3}$) despite burning crop stubble. The adverse impact was pronounced more in (RB-CS) and (CT-CS) stands accounting 38.49% porosity, 1.63 mg m$^{-3}$ Bulk density and 2.65 mg m$^{-3}$ Particle density in RB, and 37.75%, 1.64 mg m$^{-3}$ and 2.65 mg m$^{-3}$ in CT stands respectively.

Compared to the initial pH of 7.76, pH was not significantly affected by different crop establishment methods and residues management practices (Table 1). However, zero tillage (ZT) slightly lowered pH compared to other treatments with ZT + CS stands recording a pH of to 7.47 and ZT-CS stands recording 7.74. Other treatments had pH values of 7.61 (RB + CS) and 7.77 (RB-CS), 7.70 (CT+CS) and 7.80 (CT-CS).

Similarly, Electrical conductivity (EC) varied with the different stand management practices, with the highest increase observed in ZT + CS stands (0.381 dS m$^{-1}$), followed by RB + CS (0.376 dS m$^{-1}$) and CT + CS (:0.370 dS m$^{-1}$) compared to the initial EC of 0.360 dS m$^{-1}$ (Table 1). While stubble burning lead to a slight increase in EC in ZT-CS (0.372 dS m$^{-1}$), RB-CS (0.368 dS m$^{-1}$) and CT- CS (0.362 dS m$^{-1}$) stands.




CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS" – burning of crop stubbles" +CS"-retention of crop stubble.

**Figure 1.** Influences of crop stubble and tillage management on soil porosity, bulk density and particle density at 2025 in wheat cultivation.

**Table 1.** Effect of crop stubble and tillage management on post- harvest soil physical and chemical properties in wheat cultivation during 2022-2025.

| Treatments | pH | | Electrical Conductivity, dS $m^{-1}$ | | Hydraulic conductivity, mm $h^{-1}$ | | Soil organic carbon (%) | |
|---|---|---|---|---|---|---|---|---|
| | Actual estimation / % variation | | Actual estimation / % variation | | Actual estimation / % variation | | Actual estimation / % variation | |
| CT – CS | 7.80 | +0.51 | 0.360 | +0.56 | 10.40 | +3.90 | 0.347 | + 0.29 |
| ZT - CS | 7.74 | -0.26 | 0.370 | +3.35 | 10.68 | +6.69 | 0.352 | +1.73 |
| RB – CS | 7.77 | +0.13 | 0.366 | +2.23 | 10.58 | +5.69 | 0.350 | +1.16 |
| CT + CS | 7.70 | -0.77 | 0.368 | +2.79 | 10.20 | +1.90 | 0.351 | +1.44 |
| ZT + CS | 7.47 | -3.73 | 0.379 | +5.87 | 10.98 | +9.69 | 0.360 | +4.04 |
| RB + CS | 7.61 | -1.93 | 0.374 | +4.46 | 10.80 | +7.89 | 0.354 | +2.31 |
| $SE_{m\pm}$ | 0.05 | | 0.06 | | 0.08 | | 0.001 | |
| CD, 5% | NS | | NS | | 0.26 | | 0.003 | |
| Initial value | 7.76 | | 0.358 dS $m^{-1}$ | | 10.01 mm $h^{-1}$ | | 0.346 % | |

CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS"- burning of crop stubble, "+ CS"- retention of crop stubble.

**Table 2.** Effect of crop stubble and tillage management on productivity performance in wheat cultivation during 2022-2025.

| Treatment | Pooled grain yield of three years, t $ha^{-1}$ | Total biological yield, t $ha^{-1}$ | | | H.I. | | |
|---|---|---|---|---|---|---|---|
| | | 1st year | 2nd year | 3rd year | 1st year | 2nd year | 3rd year |
| CT - CS | 5.25 | 11.65 | 11.66 | 11.68 | 0.45 | 0.46 | 0.45 |
| ZT - CS | 5.60 | 11.80 | 11.82 | 12.00 | 0.47 | 0.47 | 0.47 |
| RB – CS | 5.55 | 11.65 | 11.70 | 11.91 | 0.47 | 0.47 | 0.47 |
| CT + CS | 5.32 | 11.70 | 11.72 | 11.90 | 0.45 | 0.45 | 0.46 |
| ZT + CS | 5.75 | 11.85 | 11.92 | 12.0 | 0.48 | 0.48 | 0.48 |
| RB + CS | 5.64 | 11.85 | 11.88 | 11.95 | 0.47 | 0.47 | 0.47 |
| $SE_{m\pm}$ | 0.02 | 0.07 | 0.15 | 0.21 | 0.004 | 0.006 | 0.01 |
| CD, 5% | 0.03 | 0.22 | 0.45 | 0.60 | NS | NS | NS |

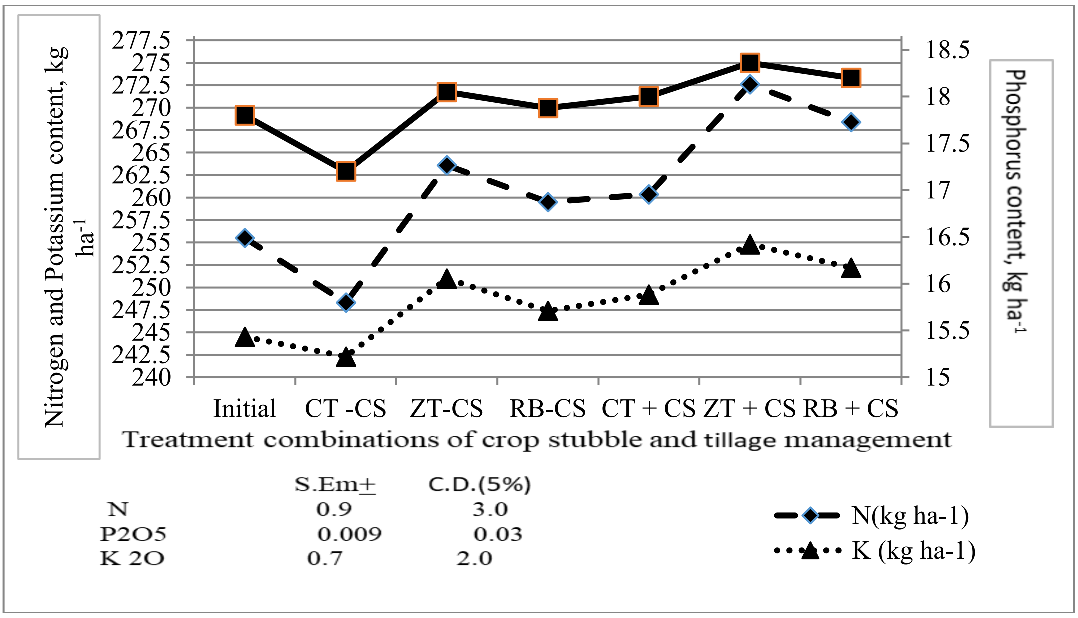
CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS"- burning of crop stubble, "+ CS"- retention of crop stubble.

Hydraulic conductivity (HC) was also higher (10.98 mm $h^{-1}$) at (ZT + CS) stands followed by (RB + CS:10.80 mm $h^{-1}$) and (CT + CS:10.20 mm $h^{-1}$) stands respectively compared with the initial HC (10.01 mm $h^{-1}$) (Table 2). While, soil HC marginally increased to 10.68 mm $h^{-1}$ in (ZT – CS) followed by (RB – CS:10.58 mm $h^{-1}$) and (CT – CS:10.40 mm $h^{-1}$) stands.

Soil organic carbon (SOC) content also increased by 0.360% at (ZT + CS) stands, significantly higher than that at (RB + CS:0.354%) and (CT +CS:0.351%) stands as compared with initial SOC (0.346 %); while marginally increased at (ZT-CS:0.352%), (RB – CS:0.350%) and (CT – CS:0.347%) stands.

Soil N, P and K content was also pronounced more at (ZT+CS) stands estimating 272.60 kg N $ha^{-1}$, 18.36 kg P $ha^{-1}$ and 254.80 kg K $ha^{-1}$,which were significantly higher than those at (RB+CS: 268.4 kg N $ha^{-1}$,18.2 kg P $ha^{-1}$ and 252.2 kg K $ha^{-1}$) and at (CT+CS:260.35 kg N $ha^{-1}$, 18.0 kg P $ha^{-1}$and 249.2 kg K $ha^{-1}$ ) stands as compared with their initial status of 255.4 kg N $ha^{-1}$, 17.8 kg P $ha^{-1}$ and 244.5 kg K $ha^{-1}$ respectively (Figure 2).

In contrast, (ZT-CS) stand marginally increased soil N (263.6 kg ha$^{-1}$), P (18.05 kg ha$^{-1}$) and K (251.0 kg ha$^{-1}$) contents, which were significantly higher than (CT-CS: N -248.3 kg ha$^{-1}$, P-17.2 kg ha$^{-1}$ and K -242.3 kg ha$^{-1}$) and at (RB-CS: N -259.5 kg ha$^{-1}$, P-17.88 kg ha$^{-1}$ and K 247.4 kg ha$^{-1}$) respectively.

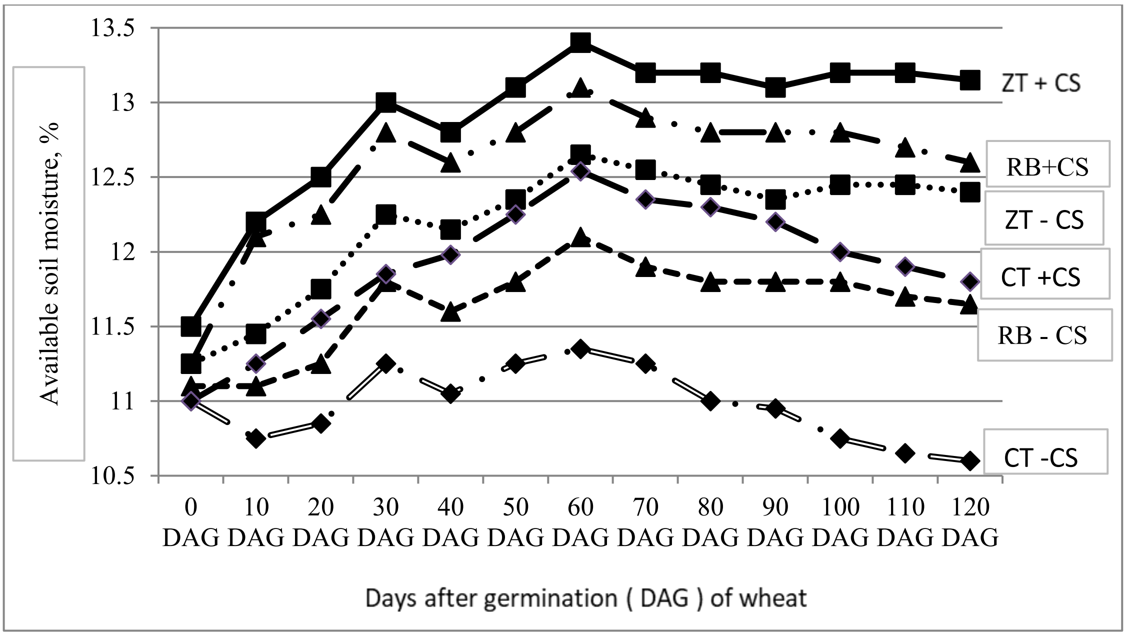



CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS" – burning of crop stubbles" +CS"-retention of crop stubble.

**Figure 2.** Influences of crop stubble and tillage management on residual soil nitrogen, phosphorus and potassium contents at 2025 in wheat cultivation.

**Available soil moisture pattern during crop growth**

Initial available soil moisture (ASM) remained around 10% across the stands, which increased with the advancement of cropping season culminating during 60 to 70 days after germination; subsequently declined towards the crop maturity (Figure 3).



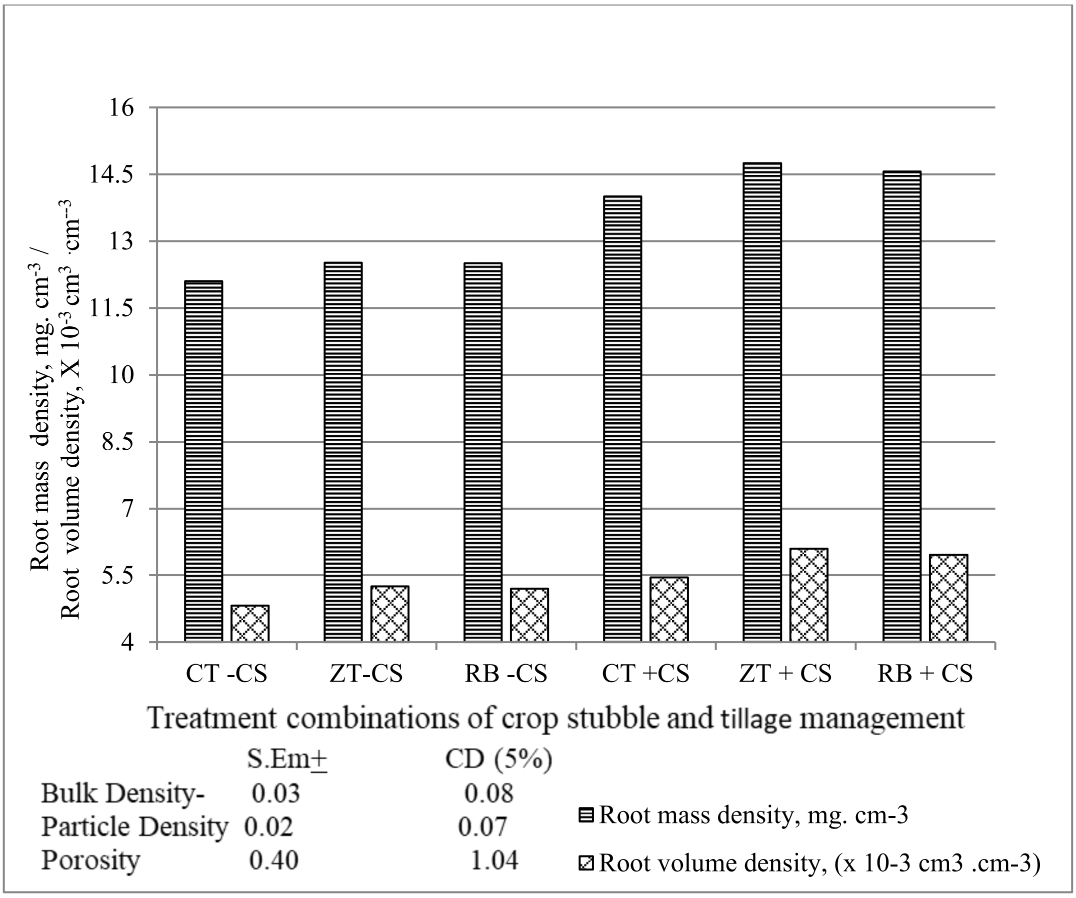

CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS" – burning of crop stubbles" +CS"-retention of crop stubble.

**Figure 3.** Influences of crop stubble and tillage management on available soil moisture pattern across crop growth stages in wheat cultivation during 2025.

Crop stubble retention at zero tillage (ZT + CS) facilitated higher ASM varying between 11.2 to 13.4% across the growth stages followed by (RB + CS: 11.0 to 13.1%) stand and at (CT+CS:10.75 to 12.54%) stand. On the other hand, ASM were relatively lower at (ZT-CS: 10.95 to 12.65%), (RB-CS:10.5% to 12.1%) and (CT-CS:10.2% to 11.35%) stands.

## Root architecture

Root development was promoted at (ZT + CS) stands accounting root mass (14.75 mg $cm^{-3}$) and volume (6.1 x $10^{-3}$ $cm^3$ $cm^{-3}$) significantly higher than (RB + CS: root mass-14.56 mg $cm^{-3}$ and volume- 5.96 x $10^{-3}$ $cm^3$ $cm^{-3}$) stands and at (CT + CS: root mass- 14.0 mg $cm^{-3}$ and volume- 5.45 x $10^{-3}$ $cm^3$ $cm^{-3}$) (Figure 4).




CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS" – burning of crop stubbles" +CS"-retention of crop stubble.

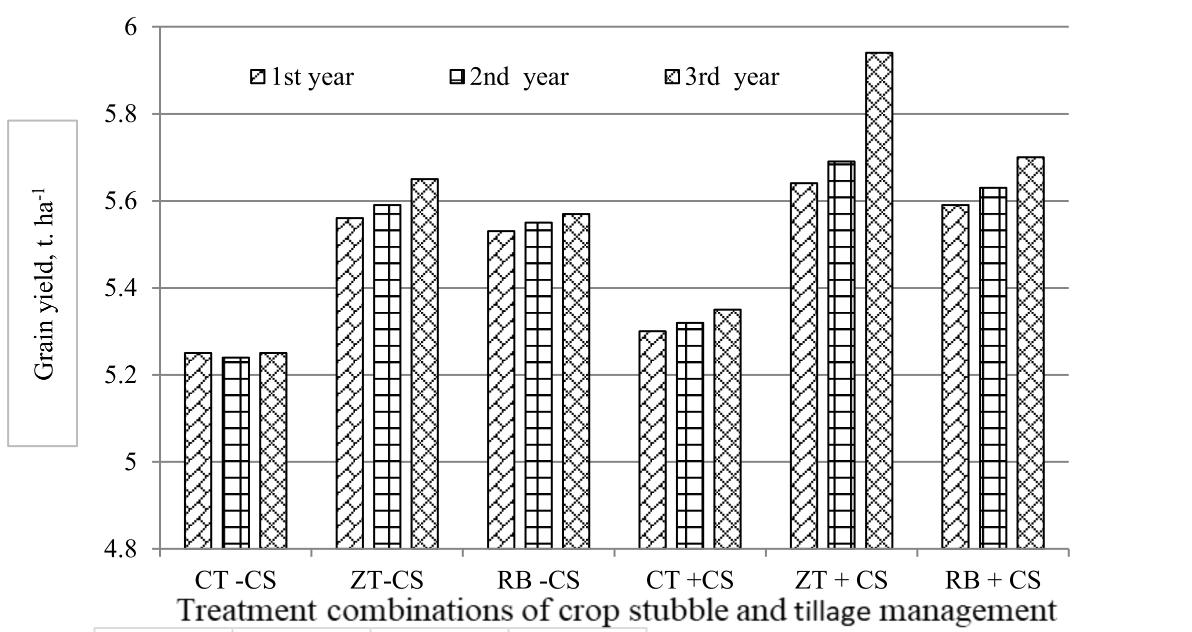
**Figure 4.** Influences of crop stubble and tillage management on root architecture (volume and mass density) at 2025 in wheat cultivation

In contrast, root growth and development was inhibited at (ZT+CS) stands accounting root mass of 12.52 mg $cm^{-3}$ and root volume of 5.25 x $10^{-3}$ $cm^3$ $cm^{-3}$ followed by (RB+CS: root mass 12.50 mg $cm^{-3}$ and root volume 5.20 x $10^{-3}$ $cm^3$ $cm^{-3}$) and (CT+CS: root mass 12.1 mg $cm^{-3}$ and root volume 4.82 x $10^{-3}$ $cm^3$ $cm^{-3}$) stands.

**Grain yield, biological yield and harvest index**

Therefore, many factors in cognizance with zero tillage and crop stubble retention could be attributed while improvement in yield parameters was interpreted for sustainably higher grain yield in wheat in this study. Recycling crop stubble residues certainly conserving substantial amount of organic matter into the soil, which could inherit consistent potential in C-sequestration in particular and overall soil health improvement in general (Kumari, et al, 2023). Consequently, ZT +CS stands produced significantly higher grain yields of 5.64, 5.69 t $ha^{-1}$ and 5.94 t $ha^{-1}$ over the year followed by RB + CS stands (5.59 t $ha^{-1}$, 5.63 t $ha^{-1}$ and 5.70 t $ha^{-1}$) and CT + CS stands (5.30 t $ha^{-1}$, 5.32 t $ha^{-1}$ and 5.35 t $ha^{-1}$ )(Figure 5).

While, grain yields at ZT- CS stands decreased to 5.56 t ha$^{-1}$, 5.59 t ha$^{-1}$ and 5.65 t ha$^{-1}$ in corresponding year, which were although significantly higher than RB-CS stands (5.5 3 t ha$^{-1}$, 5.55 t ha$^{-1}$ and 5.57 t ha$^{-1}$) and also at CT-CS stands (5.25 t ha$^{-1}$, 5.24 t ha$^{-1}$ and 5.25 t ha$^{-1}$).




| | 1st year | 2nd year | 3rd year |
|---|---|---|---|
| SEm + | 0.007 | 0.01 | 0.006 |
| CD, 5% | 0.02 | 0.03 | 0.02 |

CT- Conventional Tillage, ZT- Zero Tillage, RB- Raised bed, "-CS" – burning of crop stubbles " +CS"-retention of crop stubble.

**Figure 5.** Influences of crop stubble and tillage management on grain yields in wheat cultivation during 2022-2025.

Pooled analyses of grain yields derived over the years of study revealed maximum productivity of 5.75 t ha$^{-1}$ at (ZT+ CS) stands, significantly higher than those (5.64 t ha$^{-1}$ and 5.32 t ha$^{-1}$) at (RB+ CS) and (CT+CS) stands respectively. While, conventional practice (CT-CS) showed the lowest productivity of 5.25 t ha$^{-1}$ (Table 2).

## DISCUSSION

Traditional farm operations involving conventional tillage with heavy farm machineries and burning crop stubbles emerges as an alarming issue in wheat cultivation. These operations could threaten the *en mass* endeavour of farming community while achieving sustainable wheat production desirably.

Zero tillage with crop stubble retention ensured perceptible improvement in soil health fostering physico-chemical, nutritional and micro-biological development (Khorami, et al,2018); while, usual practice of stubble burning ended with reverse impacts of prolonged soil sickness envisaging drastic decline in soil and crop productivity. This could be attributed to formation and stabilization of substantial soil aggregates concurrence upon accumulation of organic matter as binding agent by virtue of crop residues retention (Laxmi, et al,2007).

The soil porosity comparing with initial soil status, changed significantly with different management attributed to the variations in bulk density (BD) and particle density (BD) (Aziz et al.,2013). Results showed increase of 2.1% soil porosity in (ZT +CS) stands followed by 1.1% increase in (RB+CS) stands. Contrastingly, marginal increase of 0.05% porosity was at (CT+CS) stands. Corroborating with previous reports (Laxmi, et al,2007), the study confirmed that products of microbial decomposition of crop residues namely polysaccharides and excreta / gum secretion from microorganisms could act as soil particle binding agents resulting improvement in soil aggregation and porosity (Qamar et al., 2015). Besides, retention of rice crop stubbles could also substantiate the benefits promoting micro-biotic activities within the soil matrix ensuring soil aggregate improvement. On the other hand, soil porosity decreased by 0.70% in (ZT-CS) stands; although, significantly higher than (RB-CS) (0.43%) and (CT-CS) (0.01%) stands.

Soil pH decreased maximum by 3.59% in (ZT+ CS) stands comparing with initial soil reaction, followed by (RB+CS: 1.79%) and (CT+ CS: 0.64%) stands. Reversely, it increased maximum by 0.64% at (CT-CS) followed by (RB-CS: 0.26%) stands; while lowest increase (0.12%) was at (ZT-CS) stands, instead. In fact, implication of short-term management practices could barely bring about any radical changes within soil media, that too within a span of only 3 years as they remain inherently less responsive to any short-term soil physical / mechanical manipulation (Mandal et al., 2019).

Even, nominal changes in Electrical conductivity (EC) was also visualized recording maximum increase (5.55%) in (ZT + CS) stands followed by (RB + CS: 4.44%) and (CT + CS: 2.78% ) stands compared with the initial EC. While, sight increases (3.33%, 2.22% and 0.55%) were noticed in (ZT-CS), (RB-CS) and (CT-CS) stands respectively.

Unlike EC, Hydraulic conductivity (HC) increased considerably (7.32%) in (ZT + CS) stands followed by 5.85% and 2.63% increase in (RB + CS) and (CT + CS) stands respectively compared with the initial HC (Table 2). While, crop stubble burning also increased the soil HC marginally by 4.58% in (ZT – CS) followed by 3.61% increase in (RB – CS) and mere 1.66% increase in (CT – CS) stands.

The improvement in EC and HC might be attributed to the addition of crop residues promoting soil aggregates, better root penetration and continuous channels formed by decaying root mass that could facilitate easy and uninterrupted soil water movement. While, lower HC at the event of stubble burning might be due to soil compaction restricting uninterrupted soil water flow. Stubble retention also increased soil organic carbon (SOC), maximum of 3.77% at (ZT + CS) stands, followed by at (RB + CS: 2.03%) and at (CT + CS:1.16%) stands; while stubble burning caused significant depletion of SOC at all stands accounting (ZT- CS: 1.45%), (RB – CS:1.16%) and (CT – CS: 0.29%) stands.

Thus, cumulative impacts of stubble residue retention over the years might promote C-sequestration in the system; it may also be attributed slowing down mineralization of SOM rather its supplementary conservation in the soil, instead (Mandal et al, 2019). Therefore, the study may advocate either replenishment of SOC through stubble retention, or diminishing SOC losses through zero tillage aiming at avoiding adverse impacts on soil health.

Residual soil NPK contents upon critical interpretation showed considerable increase at (ZT + CS) stands by 7.57% N, 2.53% P and 3.62% K, respectively, significantly higher than those (1.50% N, 11.40% P and 0.57% K) at (CT+CS) stand and also those (5.46% N, 1.12% P and 1.46% K at (RB+CS) stands as compared with their initial status (Figure 2). In contrast, their substantial depletion was noticed at (CT-CS) stands; although significantly higher at (ZT-CS) stands and at (RB-CS) stands.

Therefore, merits of zero tillage with crop stubble residues were also reported as prime constituent of CA balancing the carbon-nutrients ratios in soil health (Huang, et al, 2018). As these two practices could maintain ambient soil environment energizing microbial activities to mobilize decomposition and subsequent mineralization of SOM (Rani, et al, 2019).

Nonetheless, a different view could be explored explaining reduction in weed pressure at the event of delayed emergence of less weeds in undisturbed soil conditions restricting incidental nutrient mining (Yaduraju and Mishra, 2002). In addition, relatively soft and moist surface soil could facilitate early germination / emergence of wheat seed getting them imbibed with considerable weed smothering ability following an immediate ‘head start’ of wheat seedling over weeds. Substantial nutrients loss was also reported to have been incurred on stubble burning accounting around depletion of 90% of N and S, and 15-20% of P and K in rice (NAAS.2017).

Critical observations showed their significant influences on ASM during crop growth (Das, et al, 2018). Thus, ASM increased by 2.4% at (ZT + CS) stands followed by (RB + CS: 2.1%) and (CT+CS:1.1%) stands (Yang et al., 2016). On the other hand, burning stubble depleted ASM at (RB-CS) and (CT-CS) stands unlike (ZT-CS) stands. Where, soil crust formation with low soil aggregation happened resulting relatively impermeable soil layer by sealing micro-pores, thus infiltration and moisture storage ability of the soil declined substantially (Subrahmaniyan, et al, 2024).

Root development was also prompted substantially at (ZT+CS) stands, attributed to around 5% more root mass and 12% more root volume than other stands (Kumari, 2023). Intensive tillage could typically create multi-avenues facilitating faster water lose, an eventual consequence of higher degrees of soil porosity and surface roughness that could expose more surface areas aggravating evaporation losses particularly. Besides, excess water accumulation at the rhizosphere zone at the event of soil saturation at CT stands could also cause root stunting due to rapid N loss upon leaching and denitrification (Erenstein and Laxmi 2008).

As a result, wheat productivity at (ZT+CS) stands increased progressively by 1.44%, 1.79% and 5.13% during 1st, 2nd and 3rd year respectively compared with (ZT- CS) stand (Mazzoncini et al,2011). Nonetheless, (ZT+CS) stand while comparing with almost stagnant productivity at (CT-CS) achieved 7.43%, 8.59% and 13.14% more productivity during 1st, 2nd and 3rd year respectively (Figure 5). Besides, implications of integrating zero tillage and crop residues across the year could also be envisaged with 0.89% increase in grain yield in the second year, which was furthered to 4.39% in the third year compared with that in the first year, respectively. Thus, the present investigation could logically contradict earlier studies reporting demerits of crop stubble residues incorporation (Jin and Wu, 2021).

The study also confirmed the development of soil health at (ZT + CS) stands; although, eliminating the adversity caused due to conventional practices would require considerable passage of times regaining optimum soil health to pronounce far reaching consequences (Feng, et al, 2024).

## CONCLUSIONS

The present study addressed two salient CA protocols, tillage and crop residue management in RWCS system during 3 consecutive years. Couple of logical inferences may be emanated aiming at the sustainable crop productivity and soil health. Firstly, conventional tillage and usual practice of burning crop stubbles may be avoided. Secondly, zero tillage in cognizance with crop stubble retention may be adopted as the viable agro-management for soil amelioration. And lastly, integration of these two practices needs to remain instrumental synchronizing the dynamic soil-plant-water equilibrium for sustainable system productivity and farm profitability.

Adoption of this technology could incur no additional cost as one of the component technologies, no-cost zero tillage could substitute cost-intensive conventional tillage, while usual practice of stubble burning could be avoided with another no-cost component technology, stubble retention. However, there might have the challenges in transition from traditional farm operations, which could be resolved by visualizing the agro-ecological benefits while implementing this technology. In addition, there might have no limitation in adopting this technology as no additional skill or agro-inputs is required to be facilitated to the farmers.

## Recommendation

Therefore, in view of the above results and observations, the study could recommend that farmers should not plough soil, they should commence sowing sequential crop in zero tillage condition, instead . Nonetheless, they may abstain from burning previous crop stubble; those stubbles should be left in the field, allowing *in situ* incorporation within soil, instead. Consequently, they could realise the sustainable improvement in crop production and soil health as well.

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