



RESEARCH ARTICLE

Effect of conservation tillage on soil penetration resistance, bulk density, porosity and yield of rice (*Oryza sativa*) in rice-based cropping system

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Abstract

Conservation tillage has gained momentum as a sustainable alternative to conventional puddling in rice-based cropping systems, particularly in heavy-textured soils prone to structural degradation. The experiment was conducted during 2024-2025 at the Tamil Nadu Rice Research Institute, Aduthurai, to evaluate the impact of various conservation tillage methods on soil physical properties-namely, bulk density, porosity, penetration resistance and grain yield of rice (*Oryza sativa* L.) across three consecutive cropping seasons. Twelve treatment combinations were evaluated, including transplanted rice (TPR), non - puddled transplanted rice (NPTR) and direct - seeded rice (DSR), each under three fertiliser levels (100 %, 75 % and 50 % of the recommended dose of fertilisers - RDF), with and without microbial consortia (MC) containing phosphate - solubilising bacteria, potassium - releasing bacteria, zinc - solubilising bacteria and *Azospirillum* spp. The study revealed that conservation tillage with MC significantly influenced soil physical properties and rice yield. T₆ (NPTR with 100 % RDF + MC) had the lowest bulk density (1.40 Mg m⁻³) at the end of the third season, whereas T₁ (TPR with 100 % RDF) maintained the highest bulk density (1.53 Mg m⁻³), indicating less structural improvement. Soil porosity improved across all treatments, with T₆ achieving the highest porosity (52.1 %), representing a 12.28 % increase over the initial value. The mean soil penetration resistance at harvest under T₆ had the lowest (135 kPa) at 0–20, 20–40 and 40–60 cm depth in all three seasons. Grain yield was significantly enhanced in T₆ (6028 kg ha⁻¹), followed by T₂ (5932 kg ha⁻¹) and T₁₀ (5922 kg ha⁻¹). Hence, the integration of MC with reduced tillage offers a viable strategy to improve soil physical quality and nutrient efficiency by supporting long-term agricultural sustainability.

Keywords: bulk density; infiltration; percolation; puddling; soil penetration resistance

Introduction

Rice (*Oryza sativa* L.) is one of the worlds' most important staple food crops. India, as a major rice producer, alone contributes 30 % of the total area and 22 % of the total production globally (1). The Cauvery delta region, a vital agricultural area in southern India, has a long history of rice cultivation, providing staple food for millions of people and being cultivated on about 1.5 M ha, which accounts for almost 10–15 % of Indias' total rice production area (2). Fertile alluvial soils and consistent irrigation from the Cauvery River allow for two rice crops annually during the kharif (monsoon) and rabi (winter) seasons, supporting a dominant rice - rice cropping system (3).

However, the Cauvery delta also faces several challenges, including soil degradation, declining fertility, inefficient water management and increasing environmental concerns due to

overreliance on rice monoculture (4). Rice cultivation is often considered incomplete without puddling because it creates ideal conditions for rice growth. Traditional puddled transplanted rice (TPTR) systems, often dependent on high chemical inputs, have negatively impacted soil physical properties by increasing bulk density and reducing porosity (5). Moreover, puddling is associated with higher methane emissions, water wastage and compaction that elevates soil penetration resistance, thereby impeding root growth and water infiltration. These issues have prompted the need for alternative farming practices that mitigate environmental impact, restore soil health and sustain rice production in the region.

Resource conservation technologies (RCTs), such as non - puddled transplanted rice (NPTR) and direct - seeded rice (DSR), have emerged as viable alternatives to traditional puddling.

These practices aim to reduce soil disturbance, improve soil structure and enhance water and nutrient management, ultimately leading to better soil health and productivity. Integrating with microbial consortia (MC) - including phosphate-solubilising bacteria (PSB), potassium-releasing bacteria (KRB), zinc solubilising bacteria (ZSB) and *Azospirillum* spp. can supplement and partially replace up to 25 % of chemical fertiliser inputs (6). These microbes enhance nutrient availability through mechanisms such as solubilization of essential nutrients, thereby supporting sustainable agriculture.

Together, conservation tillage and MC improve soil physical conditions by reducing bulk density, increasing porosity, lowering penetration resistance and fostering soil aggregation. These changes are critical for enhancing soil organic carbon (SOC) and optimising the rhizosphere environment for plant growth. Therefore, the present study aims to evaluate the effect of conservation tillage practices, with and without MC, on soil bulk density, porosity, penetration resistance, yield attributes and grain yield of rice under the rice-rice cropping system in the Cauvery delta region.

Materials and Methods

Experimental site

Field experiments were conducted at the North Farm of the Tamil Nadu Rice Research Institute (TRRI), Aduthurai, Tamil Nadu, over three consecutive cropping seasons - *Navarai*, *Kuruvai* and *Thaladi* - spanning from January 2024 to March 2025. The experimental field is located in Tamil Nadus' Cauvery Delta Agro-climatic Zone with the coordinates of 11° 01' N and 79° 48' E with an altitude of 19.5 m above mean sea level. The analytical results of the initial soil sample are given in Table 1.

Experimental details

The experiment was laid out in a randomised block design (RBD) with 12 treatments replicated thrice. These treatments included two resource conservation technologies - NPTR and DSR,

Table 1. Soil physico - chemical properties of the experimental field

Physical properties	
Clay (%)	46.5
Silt (%)	23.3
Sand (%)	27.8
Texture	Alluvial clayey
Chemical properties	
pH	7.7
EC (dS m ⁻¹)	0.34
Organic carbon (%)	0.31
Available nitrogen (kg ha ⁻¹)	276
Available phosphorus (kg ha ⁻¹)	45
Available potassium (kg ha ⁻¹)	323

Table 2. Treatment details of the experiment

T ₁	Transplanted rice (TPR) with 100 % RDF
T ₂	Transplanted rice (TPR) with 100 % RDF + Microbial consortia (MC)
T ₃	Transplanted rice (TPR) with 75 % RDF + Microbial consortia (MC)
T ₄	Transplanted rice (TPR) with 50 % RDF + Microbial consortia (MC)
T ₅	Non - puddled transplanted rice (NPTR) with 100 % RDF
T ₆	Non - puddled transplanted rice (NPTR) with 100 % RDF + Microbial consortia (MC)
T ₇	Non - puddled transplanted rice (NPTR) with 75 % RDF+ Microbial consortia (MC)
T ₈	Non - puddled transplanted rice (NPTR) with 50 % RDF+ Microbial consortia (MC)
T ₉	Direct seeded rice (DSR) with 100 % RDF
T ₁₀	Direct seeded rice (DSR) with 100 % RDF + Microbial consortia (MC)
T ₁₁	Direct seeded rice (DSR) with 75 % RDF + Microbial consortia (MC)
T ₁₂	Direct seeded rice (DSR) with 50 % RDF + Microbial consortia (MC)

compared against conventional PTR. Treatments also varied in nutrient management, combining conventional fertiliser applications with or without MC, to assess the potential reduction in chemical fertiliser use. The study used rice varieties ADT 57 and ADT 59 across three cropping seasons. The treatment details are provided in Table 2.

Experimental materials

Direct - seeded rice (DSR)

In the DSR system, field preparation initially included dry ploughing, two passes of cultivator, three passes of rotavator, followed by land levelling. Seeds were directly sown using a drum seeder at 20 × 10 cm spacing. The varieties ADT 57 and ADT 59 were bio - primed with PSB, KRB, ZSB and *Azospirillum* spp. at 125 mL ha⁻¹. Weed management involved the application of pre - emergence herbicide, Pendimethalin at 3.3 L ha⁻¹ and early post - emergence, Novlect at 1.2 L ha⁻¹. Irrigation was managed via the Alternate wetting and drying (AWD) method at key growth stages. Fertilisation included bio-fertilisers at 500 mL ha⁻¹ and inorganic fertilisers (150:50:50 kg ha⁻¹ N: P₂O₅:K₂O) applied in four splits: basal, tillering, panicle initiation and flowering and modified according to the treatment structure.

Non-puddled transplanted rice (NPTR)

For NPTR, field preparation included dry ploughing, single pass of cultivator, two passes of rotavator and land levelling, with application of non-selective herbicide, glyphosate at 10 mL L⁻¹ for weed control before transplanting. Transplanting was done using a self-propelled transplanter with mat-type seedlings. Seeds were bio-primed with PSB, KRB, ZSB and *Azospirillum* spp. and transplanted at 20 × 17 cm spacing. Weed management followed was similar to DSR, with pre-emergence herbicide, Pretilachlor at 1.5 L ha⁻¹ and early post-emergence, Novlect at 1.2 L ha⁻¹. Irrigation was managed using AWD, maintaining a 5 cm water depth. Fertiliser application is the same as practised in DSR.

Puddled transplanted rice (PTR)

In PTR, field preparation initially involved dry ploughing, 2 passes of cultivator, 3 passes of rotavator and puddling using a power tiller, followed by land levelling. Conventional flood irrigation was followed to a depth of 5 cm until maturity. Manual transplanting was done 21 days after seedling growth with a spacing of 20 × 15 cm. The same bio-priming treatments were followed as in DSR and NPTR. Weed management involved application of pre-emergence herbicide, Pendimethalin at 3.3 L ha⁻¹ and early post-emergence, Novlect at 1.2 L ha⁻¹ followed by hand weeding at 45 DAT (days after transplanting). Fertiliser application is the same as practised in DSR and NPTR. A detailed comparison of the field operations of DSR, TPR and NPTR was given in Table 3.

Observation taken

Table 3. Comparison of field practices for DSR, NPTR and PTR Systems

Activity		DSR	NPTR	PTR
Field preparation	Cultivator	Two passes	Single pass	Two passes
	Rotavator	Three passes	Two passes	Three passes
	Ploughing	Performed	-	Performed
	Land levelling	Performed	Performed	Performed
Sowing	Drum seeder	20 x10 cm	-	-
	Self-propelled transplanter	-	20 × 17 cm	-
	Manual transplanting	-	-	20 × 15 cm
MC - PSB, KRB, ZSB and <i>Azospirillum spp.</i>	Seed treatment at 125 mL ha ⁻¹	Applied	Applied	Applied
	Seedling dipping at 125 mL ha ⁻¹	Applied	Applied	Applied
	Soil application at 500 ml ha ⁻¹ + 25 kg ha ⁻¹ of sand at basal 30 DAT and 60 DAT	Applied	Applied	Applied
Inorganic fertilizer	RDF - 150:50:50 kg ha ⁻¹ (N:P ₂ O ₅ :K ₂ O) in 4 splits	Modified according to treatment	Modified according to treatment	Modified according to treatment
	Non-selective – Glyphosate at 10mL L ⁻¹	-	Applied	-
Weed management	Pre-emergence – Pretilachlor at 1.5 L ha ⁻¹	Applied	-	Applied
	Pre-emergence – Pendimethalin at 3.3 L ha ⁻¹	-	Applied	-
	EPOE – Novlect at 1.2 L ha ⁻¹	-	Applied	Applied
	Hand weeding	45 DAT	-	-

Soil bulk density was determined using the cutting ring method, as described in previous studies (7), where the bulk density (ρ_b) is calculated using Equation 1.

$$\rho_b = M/V \text{ (Eqn. 1)}$$

where,

M is the mass of the oven-dried soil sample (g)

V is the volume of the core sample (cm³).

Soil porosity (ϕ) was determined using the following equation, where the soil particle density (ρ_s) is typically assumed to be 2.65 g cm⁻³.

$$\phi = 1 - (\rho_b/\rho_s) \text{ (Eqn. 2)}$$

where,

ρ_b is the bulk density (g cm⁻³),

ρ_s is the particle density (g cm⁻³).

Soil penetration resistance was measured using a hand-held Eijkelkamp penetrometer with an accuracy of 1000 kPa. Measurements were taken randomly across each treatment at three soil depths during key crop growth stages at active tillering (30 DAT), panicle initiation (60 DAT), flowering (90 DAT) and at harvest. Ten plants were randomly harvested in each treatment to assess the growth and yield parameters during harvest. The grain yield observed per plot was converted to kg ha⁻¹. Statistical analysis was performed using Analysis of variance (ANOVA) to assess variation among treatments. The Critical Difference (CD) at the 5 % probability level was calculated to determine significant differences between treatments (8).

Results and Discussion

Bulk density (BD)

The results revealed a significant reduction in soil bulk density (BD) across all treatments over three successive rice-growing seasons. The most notable decrease was observed in T₆ NPTR with 100 % RDF + MC, where BD decreased from 1.52 to 1.40 mg m⁻³ followed by T₂ from 1.54 to 1.46 mg m⁻³ (Table 4). This trend highlights the synergistic role of conservation tillage and microbial inoculation in improving soil physical conditions. Conventional puddling causes severe disruption of soil aggregates, leading to compaction and a dense plough pan, which hampers root proliferation, aeration and water movement. In contrast, NPTR avoids these physical disturbances, preserving the inherent soil structure. The application of MC further contributes to decompaction by stimulating biological processes that restructure the soil matrix (9).

Microbes in the consortia secrete extracellular polymeric substances (EPS), which act as natural adhesives, binding soil particles into water-stable macroaggregates. Additionally, microbial metabolites such as glomalin-related soil proteins and root exudates reinforce the structural integrity of soil aggregates, resulting in enhanced pore space and reduced bulk density (10, 11). Moreover, microbial activity enhances root growth and bioturbation. As roots penetrate and die back, they leave behind macropores that further lower the bulk density. However, research indicates that application of *Anabaena providencia* MC in NPTR significantly reduced bulk density and increased infiltration rates, reinforcing the role of microbial inoculants in

Table 4. Impact of conservation tillage on soil bulk density at three seasons

Treatments	Initial BD	BD at the end of the 1 st season	BD at the end of the 2 nd season	BD at the end of the 3 rd season
T ₁ - Transplanted Rice (TPR) with 100 % RDF	1.55	1.55a	1.54a	1.53a
T ₂ - Transplanted Rice (TPR) with 100 % RDF + MC	1.54	1.48e	1.47e	1.46e
T ₃ - Transplanted Rice (TPR) with 75 % RDF + MC	1.53	1.47f	1.46f	1.45f
T ₄ - Transplanted Rice (TPR) with 50 % RDF + MC	1.51	1.50c	1.50c	1.49c
T ₅ - Non - Puddled Transplanted Rice (NPTR) with 100 % RDF	1.53	1.53b	1.53a	1.50a
T ₆ - Non - Puddled Transplanted Rice (NPTR) with 100 % RDF + MC	1.52	1.42h	1.41h	1.40h
T ₇ - Non - Puddled Transplanted Rice (NPTR) with 75 % RDF + MC	1.51	1.48e	1.47e	1.44g
T ₈ - Non - Puddled Transplanted Rice (NPTR) with 50 % RDF + MC	1.49	1.49d	1.48d	1.47f
T ₉ - Direct Seeded Rice (DSR) with 100 % RDF	1.51	1.54a	1.52b	1.52b
T ₁₀ - Direct Seeded Rice (DSR) with 100 % RDF + MC	1.52	1.46g	1.45g	1.44g
T ₁₁ - Direct Seeded Rice (DSR) with 75 % RDF + MC	1.51	1.49d	1.48d	1.45e
T ₁₂ - Direct Seeded Rice (DSR) with 50 % RDF + MC	1.52	1.50c	1.50c	1.49d
SED	0.02	0.012	0.015	0.016
CD (p=0.05)	0.04	0.024	0.030	0.032

Different lowercase letters denote statistically significant differences (ANOVA, Duncans' Multiple Range Test, $p < 0.05$).

improving soil structure (12). Research indicates that conservation tillage in aerobic rice systems lowered soil temperature and improved moisture retention, providing a favourable microenvironment for microbial activity and further reducing BD (13).

Soil porosity

Soil porosity increased significantly across treatments, with the highest improvement recorded in T₆ (NPTR with 100 % RDF + MC), where porosity rose by 12.28 % from the initial to the end of the third season (Table 5), followed by T₂ with a 10.94 % increase. This enhancement reflects the combined effects of reduced mechanical disturbance and active biological aggregation processes.

The minimal disturbance in NPTR systems maintains structural pores, while MC enhance porosity through biochemical and biophysical means. The EPS and polysaccharides secreted by microbes increase the cohesion between soil particles, forming larger and more stable aggregates (14). These aggregates trap air and water, forming meso and macropores that improve water infiltration and aeration. In addition, microbial colonisation of the rhizosphere leads to increased root hair formation and exudation, both of which stimulate further microbial activity and aggregate formation. Research indicates that integrating Pusa decomposer MC with aerobic rice improved porosity and root density, highlighting the role of MC in promoting favourable soil physical conditions even in less intensive systems (15). Similarly, a 30–31 % increase in populations of PSB and mycorrhizal fungi under conservation agriculture emphasises the microbial role in enhancing soil physical quality (16).

Soil penetration resistance

Soil penetration resistance (PR) values were significantly lower under T₆ compared to other treatments, serving as a reliable indicator of reduced soil compaction, which directly influences root growth, water infiltration and overall soil aeration—factors critical for optimal crop development (17). Measurements were taken across three soil depths (0–20 cm, 20–40 cm and 40–60 cm) (Fig. 1), highlighting the beneficial effects of T₆ in maintaining a less compacted and more root-friendly soil structure. The mean soil penetration resistance at harvest under T₆ had the lowest values (135 kPa) across all three depths and seasons. The significantly lower PR observed at all growth stages can be attributed to reduced mechanical disturbance and enhanced soil

biological activity, especially where conservation tillage was coupled with MC application. Conservation agriculture practices such as zero or minimum tillage are known to preserve soil structure, maintain organic matter in surface layers and reduce the risk of subsurface compaction compared to conventional puddling (18, 19). Moreover, the MC applied may have contributed to improved soil aggregation and porosity through enhanced root-microbe interactions and secretion of polysaccharides and exudates (20).

At deeper depths (20–40 cm and 40–60 cm), T₆ still exhibited comparatively lower PR values than puddled treatments, which often promote the development of a dense hardpan layer due to repeated wet tillage. This hardpan impedes root penetration and limits nutrient and water uptake (21). The reduced PR values at these depths suggest better subsoil structure and a potential for deeper root proliferation, which could improve plant resilience under water or nutrient stress conditions. These findings are consistent with previous studies indicating that reduced PR under minimum tillage or no tillage systems, combined with organic or biological amendments, leads to better root growth and water movement (22). Statistical analysis confirmed that the PR differences at the deeper depths (20–40 cm and 40–60 cm) were significant, highlighting the advantages of reduced tillage practices.

Grain yield

Yield parameter and grain yield were significantly influenced by the interaction of tillage practices, nutrient management strategies and microbial inoculation (Table 6). Treatment T₆ (NPTR with 100 % RDF + MC) recorded a consistent yield increase of 16.36, 16.63 and 17.28 % over the conventional treatment T₁ across the *Navarai*, *Kuruvai* and *Thaladi* seasons respectively (2024–25). This yield advantage is attributable to a combination of improved soil physical conditions, enhanced nutrient cycling and plant growth promotion.

Microbial consortia contribute to nutrient availability by solubilising phosphorus, mobilising micronutrients (e.g., Zn, Fe) and fixing atmospheric nitrogen. These biological processes enhance nutrient use efficiency (NUE), particularly in nutrient-depleting rice systems (7). Furthermore, MC produce plant growth regulators such as indole-3-acetic acid (IAA), gibberellic acid (GA) and cytokinin, which stimulate root elongation, tillering and panicle development. A critical factor is the production of 1-1-aminocyclopropane-1-carboxylic acid (ACC) deaminase, which

Table 5. Impact of conservation tillage on soil porosity at three seasons

Treatments	Initial porosity	Porosity at the end of the 1 st season	Porosity at the end of the 2 nd season	Porosity at the end of the 3 rd season
T ₁ - Transplanted rice (TPR) with 100 % RDF	46.5	45.3e	45.5e	46.0e
T ₂ - Transplanted rice (TPR) with 100 % RDF + MC	46.6	49.5b	50.8b	51.7b
T ₃ - Transplanted rice (TPR) with 75 % RDF + MC	46.8	48.3c	49.4c	50.4c
T ₄ - Transplanted rice (TPR) with 50 % RDF + MC	46.7	47.2d	48.1d	49.2d
T ₅ - Non - puddled transplanted rice (NPTR) with 100 % RDF	46.8	46.7e	47.7e	48.8e
T ₆ - Non - puddled transplanted rice (NPTR) with 100 % RDF + MC	46.4	50.1a	51.5a	52.1a
T ₇ - Non - puddled transplanted rice (NPTR) with 75 % RDF + MC	46.6	48.8c	50.0c	51.0c
T ₈ - Non - puddled transplanted rice (NPTR) with 50 % RDF + MC	46.2	47.9d	48.9d	50.0d
T ₉ - Direct seeded rice (DSR) with 100 % RDF	46.4	46.3e	47.2e	48.4e
T ₁₀ - Direct seeded rice (DSR) with 100 % RDF + MC	46.7	49.3b	50.5b	51.4b
T ₁₁ - Direct seeded rice (DSR) with 75 % RDF + MC	46.9	48.6c	49.8c	50.8c
T ₁₂ - Direct seeded rice (DSR) with 50 % RDF + MC	47.1	47.5d	48.5d	49.6d
SEd	0.81	0.038	0.031	0.031
CD ($p=0.05$)	1.69	0.076	0.062	0.062

Different lowercase letters denote statistically significant differences (ANOVA, Duncans' Multiple Range Test, $p < 0.05$).

Table 6. Impact of conservation tillage on productive tillers and grain yield at three seasons

Treatments	Productive tillers (No./m ²)			Grain yield (kg/ha)		
	Navarai 2024	Kuruvai 2024	Thaladi 2024 - 25	Navarai 2024	Kuruvai 2024	Thaladi 2024 - 25
T ₁	240e	252e	254e	5090e	5163e	5201e
T ₂	305b	309b	314b	5724b	5815b	5886b
T ₃	281c	287c	290c	5511c	5598c	5655c
T ₄	258d	269d	272d	5300d	5380d	5420d
T ₅	247e	256e	258e	5101e	5173e	5206e
T ₆	316a	322a	328a	5923a	6022a	6100a
T ₇	289c	292c	297c	5521c	5604c	5666c
T ₈	268d	274d	276d	5312d	5391d	5431d
T ₉	243e	254e	256e	5098e	5169e	5203e
T ₁₀	301b	305b	311b	5720b	5811b	5880b
T ₁₁	285c	290c	295c	5519c	5601c	5660c
T ₁₂	261d	270d	274d	5309d	5385d	5425d
SEd	5.0	6.0	6.5	99.0	103.0	106.5
CD ($p=0.05$)	10.0	12.0	13.0	198.0	206.0	213.0

Different lowercase letters denote statistically significant differences (ANOVA, Duncans' Multiple Range Test, $p < 0.05$).

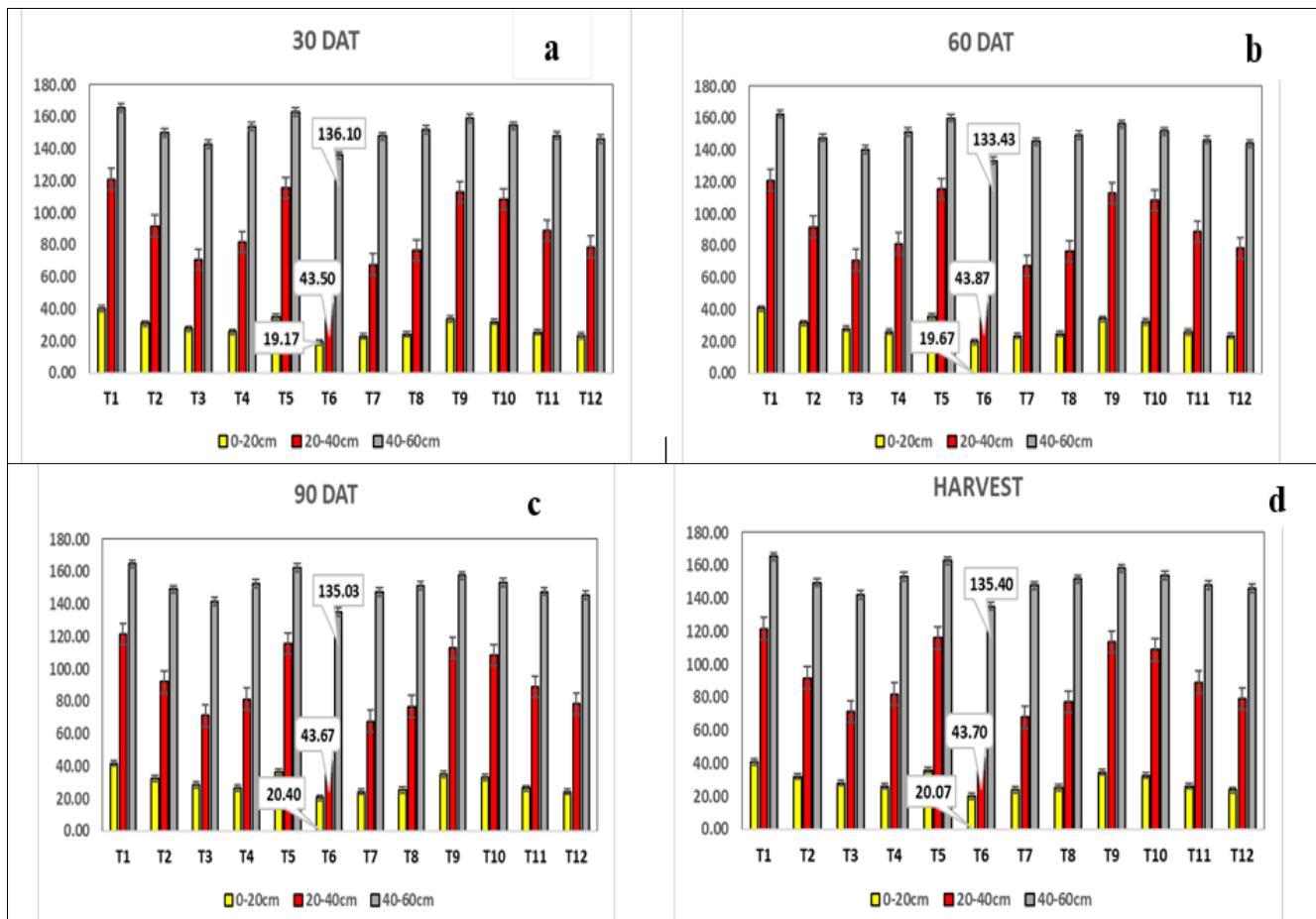


Fig. 1. Effect of conservation tillage practices on soil penetration resistance (pooled mean of three seasons. a. 30 DAT, b. 60 DAT, c. 90 DAT, d. Harvest).

breaks down the ethylene precursor ACC in plants. This action reduces stress-induced ethylene levels, allowing plants to maintain growth under suboptimal conditions such as waterlogging or nutrient deficiency. Microbial consortia in NPTR systems improved yield by enhancing NUE and promoting biomass accumulation (23). Research indicates that MC applications in aerobic rice led to significant yield gains, better energy use efficiency and higher profitability (24). Additionally, conservation tillage improved microbial biomass carbon and enzyme activities, contributing to yield improvements in rice - mustard systems.

Conclusion

The results of 3 seasonal field studies provide strong evidence that the integration of NPTR with MC (100 % RDF) significantly enhances soil physical health and rice productivity. Treatment T₆ (NPTR + 100

% RDF + MC) consistently reduced soil bulk density through improved aggregation and pore continuity, increased soil porosity and lowered soil penetration resistance across all soil depths and growth stages. These improvements contributed to better root development and water infiltration. Additionally, T₆ delivered the highest grain yields across all seasons. These positive outcomes are attributed to the synergistic effects of conservation tillage and microbial activity, which collectively reinforce soil structural integrity, improve nutrient bioavailability and mitigate stress through biochemical signalling. These findings suggest that such integrated approaches hold promise for broader application in sustainable rice-based cropping systems.

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Authors' contributions

PA conceptualized the review and prepared the initial draft. KS reviewed and corrected the structural framework of the article. SE ensured the accuracy and relevance of cited literature. RM refined the methodology and technical details discussed. KM corrected grammatical and linguistic errors. TSD enhanced the coherence and flow of the manuscript. VPH performed the final proofreading and formatting for submission.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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