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Impact of Repeated Tillage Passes on Soil Physical Characteristics under Paddy Cultivation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Paddy is predominantly cultivated under rainfed conditions. A series of tillage treatments, involving different combinations and passes of cultivators and rotavators, were evaluated to assess their impact on soil bulk density, moisture content, depth of cut, puddling index, weed population, energy use, and overall economic performance in transplanting and direct seeding systems. The results showed that both systems significantly influenced soil physical properties and field conditions. In transplanting, treatment T5 (Rotavator × 3) recorded the highest puddling index (58.2%), with better moisture retention, lower bulk density, and minimal weed regermination. While, treatment T8 (Cultivator × 2 + Rotavator × 1) in direct seeding method achieved the maximum depth of cut (92 mm) along with initial weed suppression, proving effective under dry conditions. Further, it observed that all treatments reduced weed population immediately after tillage, though regermination varied depending on the implement type and intensity. The study further stated that

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more passes of the rotavator improves puddling index, while cultivator passes enhance soil penetration under dry conditions. Energy analysis suggested that T5 found to be the most suitable option for transplanting, whereas T8 is recommended for direct seeding. The findings emphasize that farmers should adopt site-specific tillage practices to improve field efficiency, control weeds, conserve soil moisture, and optimize resource use for sustainable rice production.

Keywords: Tillage; puddling; soil physical properties; implements; cultivator; Chhattisgarh.

1. INTRODUCTION

Chhattisgarh is located in the central part of India between the latitudes of 17° 46'N - 24° 5' N and the longitudes of 80° 15' E - 84° 20' E. Its proximate position with the Tropic of Cancer has a major influence on its climate. It is landlocked by the states of Maharashtra and Madhya Pradesh on the west, Uttar Pradesh on the north, Jharkhand on the north-east, Orissa on the east, and Andhra Pradesh on the south Sprawled in an area of 135,194 sq km (Bhuarya*et al*., 2018). Chhattisgarh has diverse agro climatic zones Chhattisgarh Plains, Bastar Plateau, and Northern Hills each influencing distinct paddy cultivation practices. In the Chhattisgarh Plains paddy is grown in irrigated and rainfed fields using short to medium-duration varieties like Mahamaya and MTU-1010, with widespread use of transplanting, chemical fertilizers, and mechanization. In the Bastar Plateau, tribal farmers grow paddy under rainfed upland and midland conditions using traditional methods, indigenous varieties, and low input or organic practices (Tiwari et al., 2021). The Northern Hills feature terraced rainfed farming with drought resistant varieties, mixed cropping, and soil conservation on undulating lateritic terrain.One of the critical aspects of sustainable agriculture is effective management of soil and machinery, which heavily depends on the appropriate use of tillage operations (Verma and Dewangan, 2006). Tillage influences numerous soil physical properties including bulk density, porosity, penetration resistance, moisture retention, and aggregate stability. The type of tillage implement and the frequency of its application (i.e., the number of passes) significantly affect these soil attributes, ultimately determining crop productivity and soil health (Verma et al., 2023; Prabhu et al., 2025). However, due to repeated passes of implements such as plough, harrow, rotavator and cultivator leads to adverse outcomes such as soil compaction, structure breakdown, and reduced organic matter content. Hence, the effects of multiple passes of selected tillage implements on soil physical properties is essential for optimizing tillage practices, conserving fuel, workers productivity (Kumari et al., 2025), soil health and crop performance. Soil tillage is traditionally perceived as a necessary activity to prepare the seedbed, manage crop residues, control weeds, and incorporate fertilizers. However, the repeated mechanical disturbance of soil can alter its physical condition, sometimes leading to degradation rather than improvement. Multiple passes of tillage implements may initially improve tilth and create a fine seedbed, but excessive operations can cause compaction in the subsoil layer, decrease macro-porosity, and impair root penetration (Pandey and Dave, 2014).

For instance, while a rotavator may provide excellent seedbed preparation in a single pass, its repeated use can lead to the formation of a compacted layer or hardpan just below the tilled zone. Similarly, disc ploughs are effective in inverting and aerating the soil but may cause clod formation when used excessively. Cultivators, on the other hand, are more suited for shallow operations and weed control but have limited capacity to improve deep soil conditions (Katsvairo et al., 2002). The number of passes, therefore, becomes a critical parameter in determining the net effect of tillage on soil physical properties.

A thorough field evaluation of tillage implements with varying number of passes offers an empirical basis to establish optimum tillage practices (Patel et al., 2017). Such research is particularly relevant in regions where farmers either over till due to lack of knowledge or under-till due to resource constraints. By understanding the trade-offs involved, extension services and policymakers can promote site-specific tillage recommendations, thereby ensuring sustainable land use and enhanced crop productivity.

Tillage includes all operations of seedbed preparation that optimise soil and environmental conditions for seed germination, seedling establishment and crop growth. But over the decades, field experiments helped scientists to understand the concept of tillage management a little more finely. The conventional tillage encourages major soil erosion, high soil moisture loss, timeliness considerations, and high fuel and labour costs (Ahmed et al.,2013). Appropriate tillage practices are those that avoid the degradation of soil properties but maintain crop yields as well as ecosystem stability. Conservation tillage provides the best opportunity for halting degradation and for restoring and improving soil productivity (Khan *et al*., 2020; Shukla *et al*., 2023). Despite the recognition of tillage as a key component of soil management, there remains a gap in our understanding of how multiple passes of different tillage implements affect soil physical properties under varying agro-climatic and soil conditions. Much of the existing research has focused on single-pass operations or comparisons between tillage and no-tillage systems (Farahani et al., 2022). Limited attention has been given to how increasing the frequency of tillage impacts parameters such as bulk density, penetration resistance, moisture content, and porosity over time (Pandey & Dave, 2014).

In the field, multiple passes are often employed to achieve a desired level of soil tilth, especially in heavier or poorly drained soils. However, this practice is frequently adopted without considering the long-term consequences on soil structure and health. In many cases, excessive tillage results in reduced water infiltration, increased runoff and erosion, and deteriorated root zones. Conversely, inadequate tillage may result in poor germination, weak root establishment, and ultimately lower yields. These outcomes highlight the importance of establishing an optimal number of tillage passes for specific implements to balance soil quality and agronomic performance.

Soil degradation, particularly due to mismanagement of tillage operations, is a growing concern in both intensive and extensive farming systems. Compacted soils, reduced infiltration rates, and structural instability are becoming increasingly common problems, particularly in areas where conventional tillage practices dominate. While conservation tillage and zero-tillage have been proposed as alternatives, their adoption is still limited due to various socio-economic and technical barriers.In this context, optimizing conventional tillage practices remains a pragmatic approach for most farmers, especially in developing countries. Rather than eliminating tillage, modifying the number of passes and selecting appropriate implements based on soil response can significantly improve outcomes (Jwala et al., 2019).

The study evaluates the field performance of selected tillage implements under varying numbers of passes, focusing on their effects on key soil physical properties. Specifically, it aims to assess how disc plough, rotavator, and cultivator influence bulk density, porosity, moisture content, and penetration resistance; quantify changes after one to three passes; determine the optimum number of passes for desirable soil conditions; and compare the efficiency of these implements in modifying soil properties.

2. REVIEW OF LITERATURE

Review on paddy cultivation has extensively examined the influence of tillage intensity and establishment techniques on soil physical conditions, weed dynamics, and resource use efficiency. In this context, following literature has been reviewed; Influence of different tillage combinations have been studied by Dave and Pandey (2000). They evaluated eight tillage treatment combinations involving various tools like the mouldboard plough, 3-furrow plough, cultivator, and puddler. The results revealed that mechanized tillage required 1.52 to 2.07 times more energy than manual methods but achieved a 35% higher output-to-input energy ratio (Chaichana et al., 2014). Additionally, energy required for weeding was significantly lower (3.65 to 10.06 times) compared to manually tilled fields. Puddling index ranged between 50–65%, puddling depth between 12–15 cm, and weeding efficiency from 25–50%. Further, Dave and Saxena (2000) evaluated four tractor-operated puddling tools rotary puddler, peg type puddler, shovel type cultivator, and cage wheel in vertisol soils. The rotary puddler with two passes showed the most favorable results: highest soil dispersion (48.02%), lowest wet sieving fraction (15.11%), and minimal water percolation rate (0.295 mm/h). It was also found to be the most energy efficient, with a higher energy output-input ratio and lower specific energy requirement. Verma and Dewangan (2006) compared puddling treatments using different power sources, from traditional bullock drawn tools to tractors with cage wheels and rotavators. Puddling is an important operation to minimize soil nutrient leaching and thereby increasing the availability of plant nutrients and achieve reduced soil condition (Asenso *et al*., 2022).The tractor-operated rotavator recorded the highest weeding efficiency (98.6%) and puddling index (79.3). The fastest field preparation (9.4 h/ha) was achieved with the tractor and cultivator setup, while the rotavator had the highest energy demand (2390 MJ/ha). Saimbhi (2016) examined the puddling performance of animal-drawn implements, specifically the mouldboard and desi ploughs. The mouldboard plough was more efficient, outperforming the desi plough in terms of area coverage (by 22.09%) and weeding efficiency (by 5.6%) under submerged conditions. The combination of the mouldboard plough followed by three passes of a rotary blade puddler was both cost-effective and energy efficient, with improved puddling index. Ali (2009) explored the energy efficiency of conservation tillage tools in a rice-wheat cropping system. Zero tillage (T5) and strip tillage (T6) treatments required the least time, fuel, and energy inputs, with zero tillage being the most efficient (3.28 h/ha, 11.56 l/ha fuel use, 698.50 MJ/ha energy). In contrast, the rotavator-based system (T7) resulted in higher yields but was less energy-efficient. Zero tillage also proved to be the most cost-effective, with the lowest operational cost (Rs. 1233.77/ha).Saimbhi (2016) evaluated puddling equipment during paddy cultivation and found that the rotavator and pulverizing roller attachment produced the best puddle bed characteristics (Churpal et al., 2015). The deepest puddle bed was achieved using the pulverizing roller, while the lowest development cost was also associated with this attachment. However, conventional methods using a cultivator-planker showed higher field capacity. Kalita et al. (2020) highlighted both the advantages and drawbacks of mechanical puddling in wetland rice farming. Although mechanical puddling improves transplanting and weed control by increasing the puddling index and soil bulk density, it also negatively impacts the soil structure, reducing water infiltration and root growth potential for post-rice crops. The study emphasized that while increased puddling (IS: 11531, 1985) intensity enhances rice yield, it also deepens compacted layers and causes cracking. Interestingly, no-till mechanical transplanting yielded better than traditional puddled rice cultivation due to improved soil conditions for subsequent crops. Rangapara et al. (2017) assessed the performance of different tractor-implement combinations for seedbed preparation. The mini tractor (15 hp) proved to be more efficient and economical than higher powered tractors or power tillers (IS:9164; 1979, Shrivastava *et al*., 2010). The operational cost for the mini tractor was the lowest (Rs. 1396.44/ha), outperforming other systems in terms of draft, fuel use, field efficiency, and soil disturbance volume.

3. MATERIALS AND METHODS

The study was carried out during the kharif season of 2023–2024 jointly at the Instructional cum seed production farm, KDC College of Agriculture and Research Station, Saja, Bemetara and SV College of Agricultural Engineering and Technology and Research Station, IGKV Raipur. Raipur and Bemetara district fall in the CG plain region where the annual average rainfall is 1400mm and situated 85 km apart. The field soil was medium black vertisol which contains high nutrients, expanding and shrinkage clay. The cropping pattern was paddy followed by wheat. Before the experiment, the previous crop was wheat and harvested by a combine harvester and then the straw was burned.

3.1 Selection of Field and Implements

The experiment was conducted under paddy cultivation conditions using a Randomized Block Design (RBD) with 05 treatments and 03 replications for transplanting and dryland condition. Each experimental plot measured 20 m × 6 m (120 m²), separated by 0.5 m bunds and irrigation channels to maintain uniform water levels. To record soil properties like moisture, bulk density content of the field, three random location in selected plots has been chosen at a depth of 0–15 cm using a soil auger. Moisture Content has been determined by oven drying method at 105 °C for 24 hour while. Bulk Density has been measured using the core method.

To investigate the effect of multiple passes of tillage implements, two widely used implement i.e. an 11 tine type cultivator (8–15 cm depth) and rotavator (10–15 cm depth, L-blades) were selected to compare linear and intensive soil disturbance. Similarly, transplanting of paddy has been performed manually and mechanically. An 8-row rice transplanter was used to assess transplanting quality under varied puddle condition while seed cum fertilizer has been utilized to perform direct seeding of rice (DSR) (Rathi et al., 2019). The details of the implements and machinery have been given in Table 1.

Table 1. Details of selected implements for the study

Particulars	Name of implements and machinery		
	Cultivator	**Rotavator**	**Paddy transplanter**
Specification	11 tyne	L-type blade	8-row
Nominal width	2.2m	2.1m	1.6m
Weight	230 kg	430 kg	360kg
Power source used	47kW	47kW	3.7kW

Table 2. Design of experiments

Level	02	Manual Transplanting (PT), Direct seeding (DSR)	Parameters to be recorded
Treatment	05 each	PT- *T1, T2, T3, T4, T5* DSR- *T6, T7, T8, T9, T10*	Soil bulk density, moisture content, puddling index, depth of puddling, soil inversion.

The study was conducted using the Rajeshwari variety of rice, a commonly cultivated variety in the region. A total of 10 treatments were included, each replicated three times, to study the impact of different tillage intensities and methods under two main cultivation practices: transplanted rice and direct seeded rice (DSR) as shown in Table 2**.** The treatments involved various combinations of tillage operations using a cultivator and rotavator. For transplanted rice, five treatments were applied; i.e. T1: Cultivator (1 pass) + Rotavator (1 pass), T2: Cultivator (1 pass) + Rotavator (2 passes), T3: Cultivator (2 passes) + Rotavator (1 pass), T4: Rotavator (2 passes) and T5: Rotavator (3 passes). Similarly, under direct seeded rice, five treatments were applied i.e. T6: Cultivator (1 pass) + Rotavator (1 pass), T7: Cultivator (1 pass) + Rotavator (2 passes), T8: Cultivator (2 passes) + Rotavator (1 pass), T9: Rotavator (2 passes) and T10: Rotavator (3 passes). The independent variable in this experiment was the type and intensity of tillage treatment applied, while the dependent variables included soil parameters such as bulk density (g/cm³) to determine soil compaction. Moisture content (%): to evaluate the soil's water retention capacity post-tillage. Puddling index (%): to assess the degree of soil pulverization and water retention for transplanted conditions. Depth of puddling (cm): indicating how deep the tillage has affected the soil layer. Soil inversion (m²): to estimate the thoroughness of soil mixing and turning.

4. RESULTS AND DISCUSSION

This study aims to examine how different tillage passes of selected implements, namely a tine-type cultivator and a rotary tiller operated with tractor power, along with a self-propelled rice transplanter, affect several factors, including soil bulk density, soil moisture content, time requirements, fuel usage, yield, energy metrics, and economic aspects of various tillage practices in kharif rice farming (Alipour et al., 2012). The cultivator represents conventional linear soil disturbance, while the rotavator provides intensive pulverization and residue mixing, enabling comparison of their impacts under repeated passes. The self-propelled rice transplanter was included to evaluate how altered soil conditions influence planting efficiency and field performance (Fig.1). Additionally, the option of direct-seeded rice (Fig.2) was considered to compare transplanting with reduced-tillage establishment methods. The observations and outcomes from the experimental work of this study have been detailed in this chapter.

Fig.1. Puddling operation followed by mechanical transplanting of paddy

Fig.2. Direct seeding of rice using a seed cum fertilizer drill

4.1 Effect of Tillage Treatment on Bulk Density

Two distinct rice cultivation practices— paddy transplanted (TP) and direct seeded rice (DSR) were evaluated. For TP cultivation, puddling was carried out while DSR plots underwent dry tillage operation. For both cultivation methods, soil bulk density was measured twice: once immediately (BDi) after the tillage operation and again 15 days after sowing (BD15) or transplanting. The initial average bulk density of the experimental field across all treatments was recorded as 1.42 g/cm³.

For the TP treatments, the average bulk density immediately after puddling was found to be 1.352 g/cm³. The lowest value was recorded in T5 (Rotavator × 3) at 1.317 g/cm³, indicating better soil loosening. Further, it was followed by T4 (Rotavator × 2) at 1.347 g/cm³, T1 (Cultivator × 1 + Rotavator × 1) at 1.357 g/cm³, T3 (Cultivator × 2 + Rotavator × 1) at 1.363 g/cm³, and T2 (Cultivator × 1 + Rotavator × 2) at 1.377 g/cm³. After 15 days of transplanting, bulk density was highest in T2 (1.387 g/cm³), followed by T1 (1.377 g/cm³), T3 (1.370 g/cm³), T4 (1.367 g/cm³), and T5 (1.333 g/cm³) as indicated in Fig.3. The lower bulk density in T5 across both observation points indicates improved soil structure that may enhance root development and water infiltration (Sharma et al., 2018).These results demonstrate that tillage intensity and method significantly affect soil bulk density, which in turn influences soil health and crop performance.

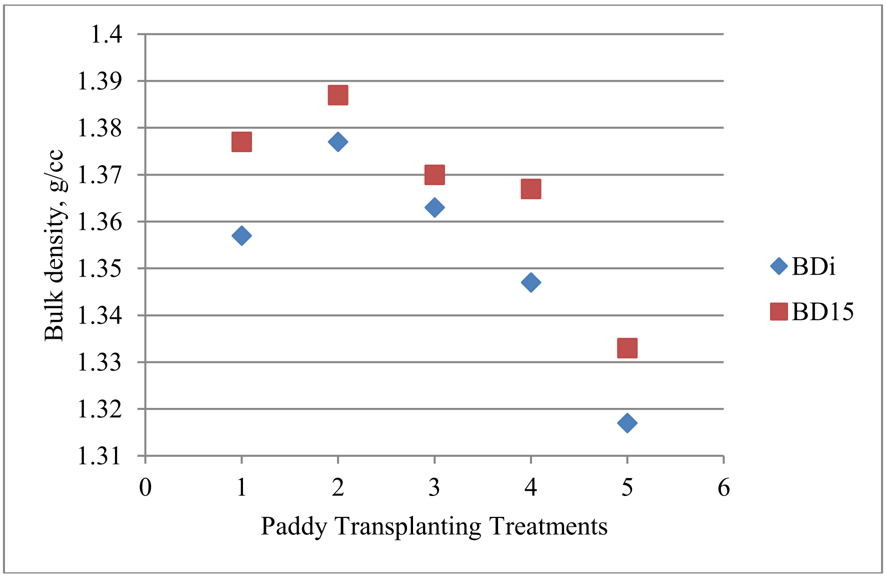

Fig.3. The change in bulk density immediate and after 15 days of puddling operation

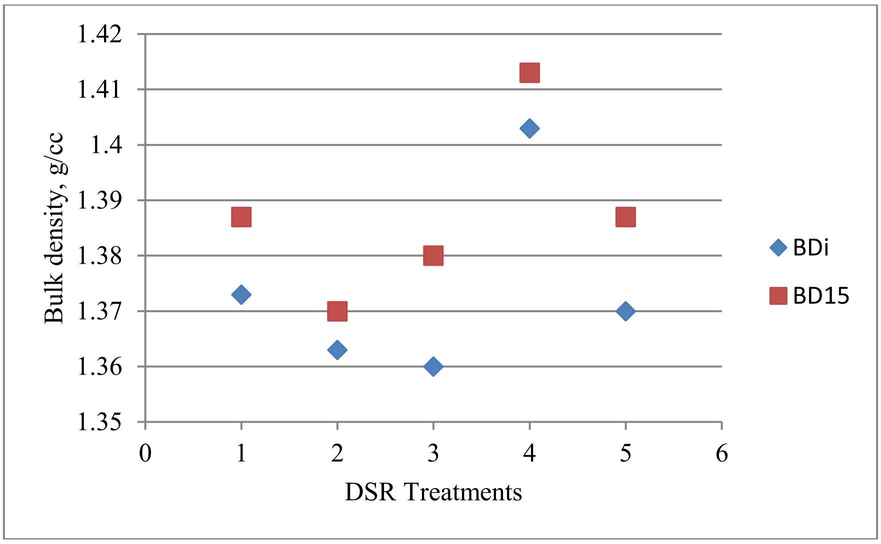

Fig.4. The change in bulk density immediate and after 15 days of tillage operation (DSR)

In the case of DSR, the average bulk density immediately after the first tillage operation was observed to be 1.374 g/cm³. The treatment T9 (Rotavator × 2) reflect the highest bulk density at 1.403 g/cm³, indicating a higher level of soil compaction as shown in Fig.4. This was followed by T6 (Cultivator × 1 + Rotavator × 1) at 1.373 g/cm³, T10 (Rotavator × 3) at 1.370 g/cm³, T7 (Cultivator × 1 + Rotavator × 2) at 1.363 g/cm³, and T8 (Cultivator × 2 + Rotavator × 1) at 1.360 g/cm³. After 15 days of seeding, the bulk density remained highest in T9 (1.413 g/cm³), followed by T10 and T6 (both at 1.387 g/cm³), T8 (1.380 g/cm³), and T7 (1.370 g/cm³). The persistently higher bulk density in T9 suggests greater soil compaction, which may adversely affect root penetration and water movement.

Among all treatments, T9 (Rotavator × 2) consistently exhibited the highest bulk density 15 days after seeding or planting, significantly exceeding all other treatments. Following T9, treatments T2 (Cultivator × 1 + Rotavator × 2), T6 (Cultivator × 1 + Rotavator × 1), and T10 (Rotavator × 3) also showed significantly higher bulk densities, although they were statistically similar to each other. Treatments T8 (Cultivator × 2 + Rotavator × 1) and T1 (Cultivator × 1 + Rotavator × 1) were statistically at par but had higher bulk densities compared to T7, T3, T4, and T5, which indicated comparatively looser soil structures (Pandey and Dave, 2014).

4.2 Effect of Tillage Treatment on Moisture Content

Soil moisture content is a critical factor influencing seed germination, root development, and overall crop performance, and it is directly affected by the type and intensity of tillage practices. The experiment revealed significant variations in soil moisture content among different tillage treatments, both immediately after field operations and 15 days later.In transplanted rice plots, immediately after puddling, the highest soil moisture was found in T5 (Rotavator × 3) at 28.95%, likely due to thorough mixing and surface sealing. It was followed by T1 (28.22%), T3 (27.70%), T4 (25.13%), and T2 (24.94%) as shown in Fig.5.After 15 days of puddling, moisture content remained highest in T5 (26.62%), followed by T1 (25.58%), T3 (23.82%), T2 (22.65%), and T4 (22.54%). These results indicate that increased tillage intensity and rotavator use in TP can enhance short-term moisture retention due to the formation of a compact plow pan and reduced percolation losses (Sharma *et al.*, 2018).

In DSR plots, the highest moisture content immediately after field operation was observed in treatment T9, with a value of 38.38%, indicating better moisture retention due to higher compaction. It was followed by T8 (37.27%), T7 (34.92%), T6 (28.03%), and T10 (25.94%). Fifteen days after the tillage operation, a similar trend in moisture content was recorded. Treatment T9 again maintained the highest moisture level at 36.45%, followed by T8 (35.39%), T7 (30.79%), T6 (25.23%), and T10 (24.26%). This pattern (Fig.6) suggests that heavier or multiple tillage passes (as in T9 and T8) may reduce infiltration and increase moisture retention in the upper soil layers.

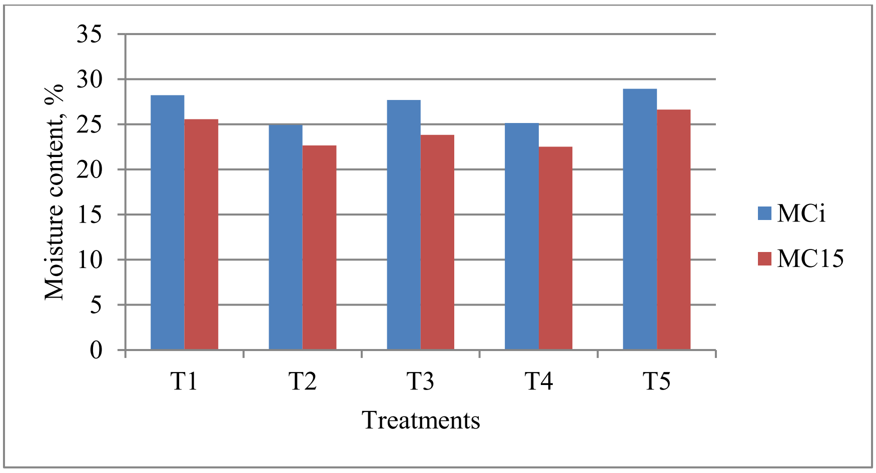

Fig.5. Soil moisture condition immediate and 15 days after transplanting

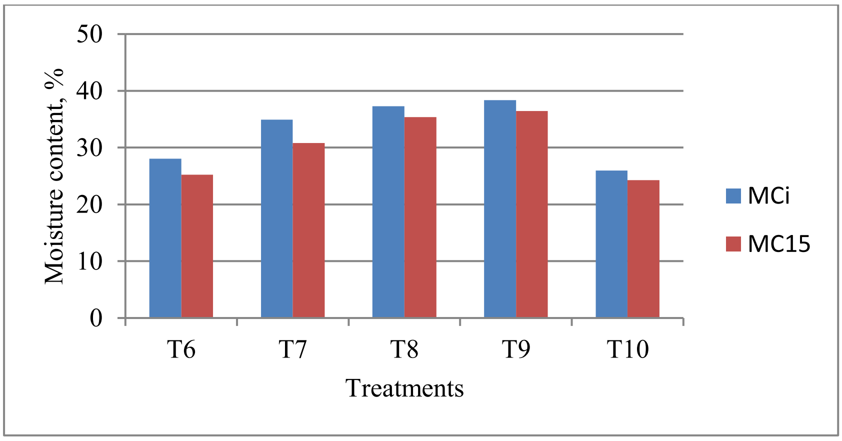

Fig.6. Soil moisture condition immediate and 15 days after direct seed sowing

The observation highlights that different tillage treatments significantly influence the soil's capacity to retain moisture, with more intensive tillage generally enhancing immediate moisture levels (Patel *et al.,* 2017). However, prolonged moisture retention also depends on the structural integrity and porosity of the soil, which vary between DSR and TP systems. Selecting appropriate tillage combinations based on soil type and cultivation method can thus optimize soil moisture management for improved crop performance.

4.3 Comparison of Bulk Density and Moisture Content

Using the critical difference (CD) values, statistically significant differences in soil bulk density and moisture content were identified among the various treatments. For bulk density measured immediately after operation (CD = 0.003), Treatment T5 showed significant differences when compared to all other treatments (T1 to T10), indicating its consistently lower bulk density. Additionally, T4 also differed significantly from treatments such as T2, T6, and T9. After 15 days (CD = 0.005), T5 maintained its significantly lower bulk density compared to almost all other treatments, with some minor significant differences also observed, such as between T4 and T9. Regarding moisture content immediately after operation (CD = 0.65%), Treatments T2 and T4 exhibited significantly lower values compared to T5, T6, T7, T8, and T9. Treatments T8 and T9 recorded the highest and significantly different moisture content levels from the others (Fig.7). After 15 days (CD = 0.91%), T2 and T4 continued to show significantly lower moisture content, while T8 and T9 again remained the highest, with their differences statistically significant. These results highlight the distinct influence of each treatment on soil compaction and moisture retention capacity.

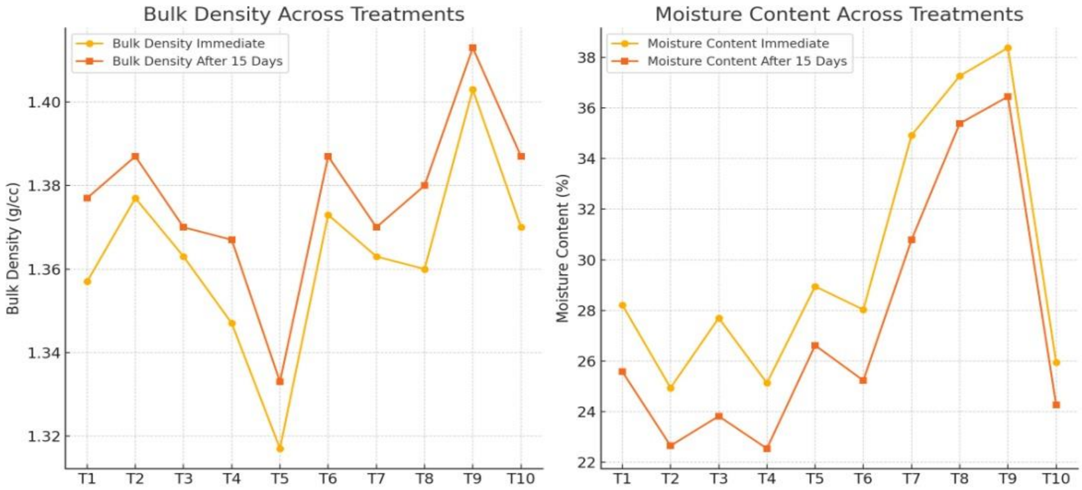

Fig.7. Varying trend of bulk density and moisture content among selected treatments

4.4 Effect of Puddling on Puddling Index

Puddling is a crucial operation in transplanted rice cultivation, primarily aimed at reducing percolation losses, improving water retention, and facilitating transplanting by creating a soft and muddy soil environment. The puddling index serves as a quantitative indicator of the degree of soil pulverization and the effectiveness of puddling, with higher values indicating better puddling quality. In the present study, the puddling index varied significantly across treatments involving different combinations and passes of cultivator and rotavator. According to the observations, the highest puddling index (58.2%)was recorded in Treatment T5 whereas 3 passes of rotavator indicated the most effective puddling among all treatments as shown in Fig.8. The lowest puddling index(44.2%)was observed intreatment T1 where single pass of cultivator followed by rotavator were performed, suggesting relatively poor soil pulverization and mixing.

Similarly, the pudlling index of the other treatments was recorded 53.7%, 51.8%, and 48.8% for T2, T3 and T4 respectively. This progression illustrates that increasing the number of rotavator passes has a more pronounced effect on the puddling index than increasing cultivator passes alone. For instance, when the cultivator pass was held constant at one (T1 vs. T2), an increase in rotavator passes from one to two significantly improved the puddling index. Similarly, when the rotavator pass was held at one (T1 vs. T3), increasing the cultivator pass from one to two also improved the puddling index, but not to the same extent as increasing rotavator passes.

These results clearly demonstrate that the level of puddling improves with the increasing intensity of tillage, regardless of the specific combination of implements used. However, rotavator passes contribute more significantly to puddling effectiveness compared to cultivator passes, likely due to the rotavator's ability to achieve finer soil tilth and better water-soil mixing.The similar findings were obtained by Dave and Pandey (2000), Dave (2004), Verma and Dewangan (2006), Kumar (2007), and Saimbhi (2016).Theyreported that increased rotavator use enhances the puddling index and improves puddling quality in transplanted rice systems.For optimal puddling performance in rice cultivation, increasing the number of rotavator passes, either alone or in combination with cultivator operations is an effective strategy to achieve higher puddling index values and better field conditions for transplanting.

4.5 Effect of Dry and Wet Tillage on Depth of Cut and Depth of Puddling

The depth of tillage whether in the form of a *cut* during dry tillage or *puddling* in wet conditions is an important parameter that reflects the effectiveness of soil penetration and loosening. It directly influences root development, water infiltration, and field preparation quality (Farahani et al., 2022). In this study, both depth of cut (dry tillage)anddepth of puddling (wet tillage) were evaluated under various tillage treatment combinations involving cultivators and rotavators.

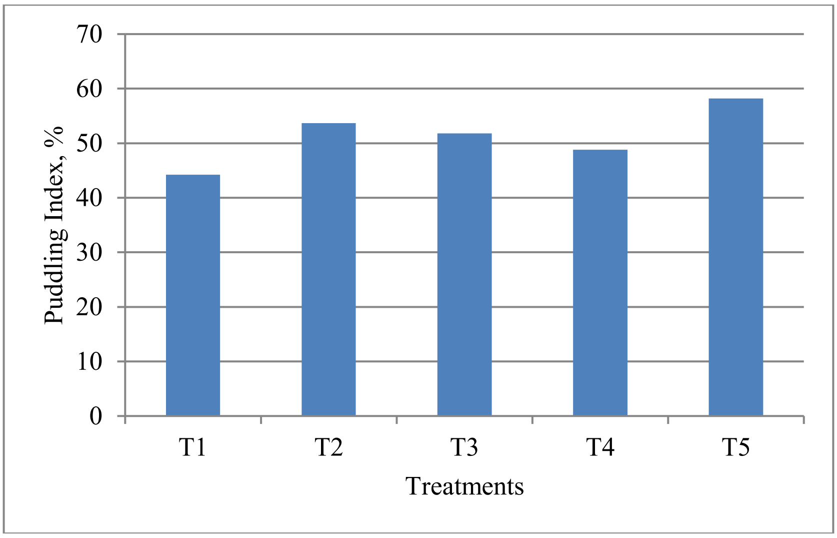

Fig.8. Effect of passes on puddling index

4.5.1 Depth of puddling

The depth of puddling among the different puddling treatments ranged from 120 mm to 149 mm. The lowest puddling depth (120 mm) was recorded in Treatment T3 (Cultivator × 2 + Rotavator × 1), despite the use of three tillage passes. In contrast, treatments with more rotavator passes, such as T5 (Rotavator × 3) and T2 (Cultivator × 1 + Rotavator × 2), recorded higher puddling depths, confirming that the number of rotavator passes significantly influences the puddling depth.For instance, T2 showed a higher depth than T1, where both had one pass of cultivator but differed in the number of rotavator passes (two in T2 vs. one in T1). Fig.9 suggests that rotavator is more effective than cultivator in achieving greater puddling depth due to its higher soil-cutting and mixing efficiency in saturated conditions (Katsvairo *et al.*, 2002). Interestingly, T3, despite having three total passes (two cultivator + one rotavator), resulted in the lowest depth of puddling, possibly due to the limited mixing capacity of the cultivator in wet conditions. These findings are consistent with those reported by Dave and Pandey (2000), Dave (2004), Verma and Dewangan (2006), Kumar (2007), and Saimbhi (2016), who also observed that more rotavator passes improve puddling performance.

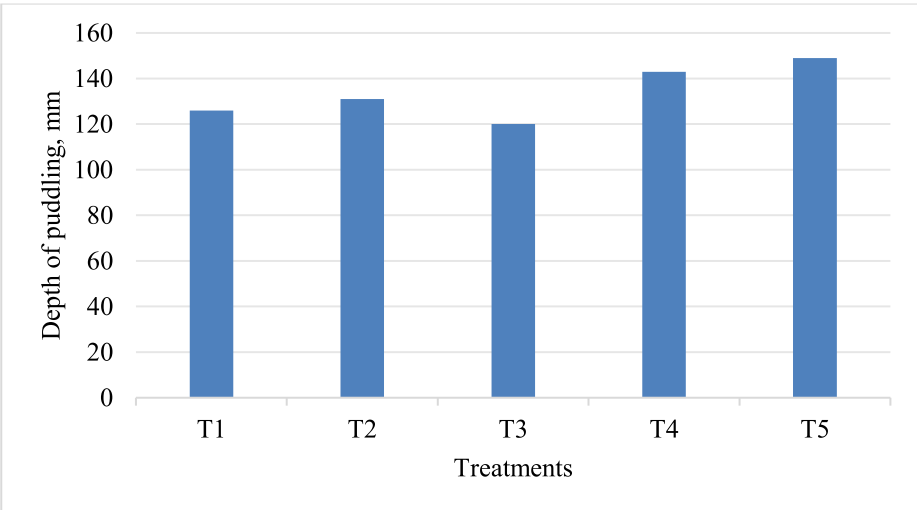

Fig.9. Effect of puddling on depth of puddling in different treatment

4.5.2 Depth of cut

For dry tillage, the depth of cut varied between 64 mm and 92 mm across treatments. The lowest depth of cut (64 mm) was recorded in Treatment T9 (Rotavator × 2), indicating that using only the rotavator, even with multiple passes, may not be as effective in achieving deeper soil penetration in dry conditions.In contrast, Treatment T8 (Cultivator × 2 + Rotavator × 1) recorded the highest depth of cut (92 mm). Fig.10 suggests that the use of the cultivator contributes significantly to increasing the depth of soil penetration during dry tillage. Cultivators, with their tines, can loosen compacted soil more effectively than rotavators, especially in dry conditions.Interestingly, T7 (Cultivator × 2 + Rotavator × 1), which also involved three passes like T8, recorded a lower depth of cut, possibly due to variability in field conditions or operator efficiency. However, the general trend indicates that the inclusion of cultivator passes results in deeper cuts, enhancing soil preparation for seeding or transplanting.The results clearly illustrate that rotavator is more effective in increasing the depth of puddling under wet conditions (Verma *et al.*, 2023), while cultivator use contributes more to the depth of cut under dry conditions. The number and combination of tillage passes play a critical role in determining soil penetration depth. For optimal field preparation, the choice and sequence of tillage implements should be tailored according to soil moisture conditions and desired tillage outcomes.

4.6 Effect of Different Treatments on Weed Population

Tillage plays a significant role in managing weed populations by disrupting weed root systems, burying weed seeds, and exposing them to desiccation. In this study, the impact of different dry and wet tillage treatments on weed population density (weeds/m²) was assessed before and after operations, as well as the extent of weed re-germination over time.Across all treatments, a reduction in weed population was observed immediately after tillage—both in dry and wet conditions—when compared to the initial pre-tillage state (Powar*et al.*, 2020). This confirms the general effectiveness of tillage in providing immediate weed suppression.

Under wetland treatments, the highest weed control efficiency was observed in Treatment T5, followed by T2, T4, T3 and T1. The effectiveness of T5 can be attributed to the intensive soil churning by the rotavator, which buries and damages weed propagules and inhibits their regrowth.Among the dry tillage treatments, the highest weeding efficiency was recorded in Treatment T8 (Cultivator × 2 + Rotavator × 1), followed by T7 (Cultivator × 1 + Rotavator × 2), T10 (Rotavator × 3), T9 (Rotavator × 2), and T6 (Cultivator × 1 + Rotavator × 1). The superior performance of T8 can be attributed to the effective mechanical action of multiple cultivator passes combined with rotavator use, which disturbed the soil deeply and uprooted more weed biomass.

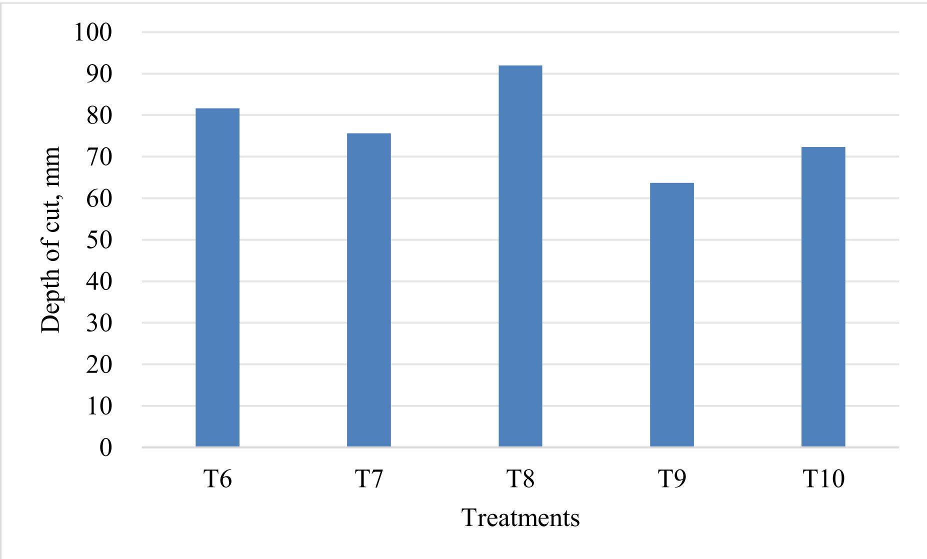

Fig.10. Effect of rotavator on depth of cut in different treatment

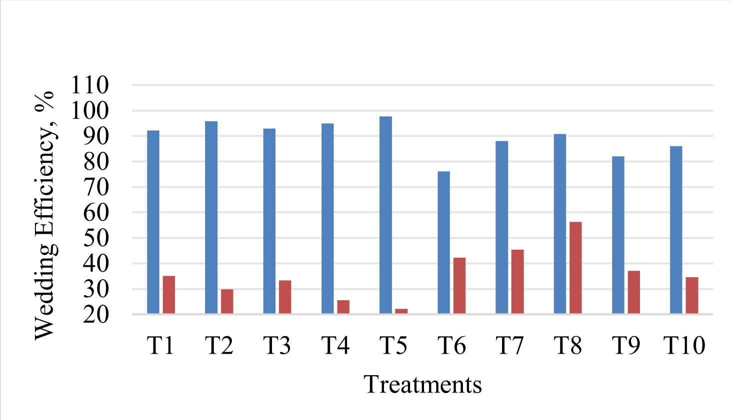

Fig.11. Effect of soil inversion in different treatment

4.6.1 Weed re-germination

Weed re-germination was monitored after the initial reduction, and notable differences were observed among treatments. Treatment T5 showed the lowest weed re-germination, indicating sustained suppression over time due to thorough puddling. On the contrary, T8 exhibited the highest re-germination, suggesting that despite high initial weeding efficiency, conditions in this treatment favored weed re-emergence—possibly due to a finer tilth and surface moisture that facilitated new seedling growth (Victor *et al*., 2020, Prabhu*et al.*, 2025).

The overall trend of weed re-germination across treatments was follows:T5 < T4 < T2 < T3 < T10 < T1 < T9 < T7 < T6 < T8 as seen in Fig.11.These results align with earlier research by Dave and Saxena (2000), Kumar, (2007), and Ali, (2009), who also found that more intense puddling and multiple rotavator passes are effective in reducing both immediate and delayed weed growth.The study revealed that both dry and wet tillage treatments significantly reduce weed populations initially. However, the long-term effectiveness depends on the intensity and type of tillage equipment used. Treatments involving multiple rotavator passes (like T5) were most effective in minimizing weed re-germination, making them suitable for long-term weed control in transplanted rice systems (Yadav et al., 2013). Conversely, dry tillage treatments with less aggressive soil disturbance showed higher weed re-growth, emphasizing the need to balance initial control with follow-up weed management strategies.

5. CONCLUSIONS

The study concluded that tillage intensity and the type of implements used strongly influence soil physical properties, water retention, puddling effectiveness, and weed management in paddy cultivation. The following major conclusion have been draw from the study;

1. Repeated rotavator passes significantly reduced bulk density and increased moisture retention compared to cultivator-rotavator combinations. Treatments with three rotavator passes (T5) recorded the lowest bulk density, highest moisture content, and highest puddling index (58.2%).
2. Increasing the number of puddling passes enhanced puddling index (up to 58.2%), depth of puddling (120–149 mm), and depth of cut (64–92 mm), indicating better soil tilth for transplanting.
3. Treatments with multiple rotavator passes, particularly T5 (Rotavator × 3) and T9 (Rotavator × 2) found to be enhanced soil moisture retention and maintained favorable compaction levels, while treatments T7, T3, T4 and T5 resulted looser soil structures conducive to root growth.
4. Number of passes of rotavator significantly increased puddling depth (120–149 mm) and improved puddling index in wet soil preparation. Similarly, cultivator passes contributed more to depth of cut during dry tillage (64–92 mm).
5. Multiple rotavator passes (T5), achieved the highest immediate and long-term weed suppression, whereas dry tillage with combined cultivator and rotavator passes (T8) allowed higher re-germination.
6. Treartment T5 maintained the lowest bulk density immediately and 15 days after operation, while T8 and T9 retained the highest moisture levels, underscoring the

role of tillage intensity in balancing compaction and moisture conservation.

In nutshell, treatments involving multiple rotavator passes were most effective in optimizing soil physical condition, puddling quality, moisture retention, and weed control, whereas combining cultivator and rotavator passes enhanced dry tillage penetration and initial weed suppression.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We would like to clarify that the research presented in our manuscript has been entirely conducted by us. All data were recorded during the actual experiments performed as part of this study. Artificial Intelligence (AI) was not used for analysis, interpretation, or generation of results. AI tools were only used for language correction to improve readability. We assure you that the scientific content, methodology, and conclusions are fully based on our own experimental work.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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