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Research Article

Tillage Practices and Nitrogen Fertilizer Rates Affect Soil Physical Properties and Grain Yield of Lowland Rice (Oryza sativa L.) in Ayamelum, Anambra State, Nigeria

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Abstract

Suboptimal soil tilth and poor nitrogen use efficiency limit lowland rice (Oryza sativa L.) productivity in southeastern Nigeria. A field study was conducted at the Lower Anambra Irrigation Project (LAIP) Research Farm, Omor, Ayamelum Local Government Area, Anambra State, Nigeria, during the 2025 wet cropping season (June–October) to evaluate the interactive effects of tillage systems and nitrogen levels on soil bulk density and rice grain yield. The experiment was laid out in a Split-Plot Design with three replications. Main-plot treatments comprised three tillage practices: zero tillage (ZT), minimum tillage (MT), and conventional puddling (CP), while sub-plot treatments consisted of four urea-nitrogen rates (0, 60, 120, and 180 kg N ha−1) tested on the rice variety FARO 44. Soil physical parameters (0–15 cm depth) and yield components were subjected to Analysis of Variance (ANOVA), and treatment means were separated using Least Significant Difference (LSD) at $p \leq 0.05$. Results revealed a significant ($p < 0.05$) interaction between tillage and nitrogen rate on grain yield. Conventional puddling reduced soil bulk density by 14.8% (from 1.42 to 1.21 g cm−3) and increased water retention compared to zero tillage. The combination of CP × 120 kg N ha−1 produced the highest productive tiller count (342 tillers m−2) and maximum paddy yield (5.64 t ha−1), outperforming ZT × 0 kg N ha−1 (1.92 t ha−1) by 193.8%, while showing no significant difference from CP × 180 kg N ha−1 (5.71 t ha−1). Conventional puddling combined with 120 kg N ha−1 is therefore recommended for sustainable lowland rice production in the Omor irrigation zone.

Keywords: *Oryza sativa, split-plot design, puddling, nitrogen rate, soil bulk density, FARO 44.*

1. Introduction

Rice (Oryza sativa L.) is the fastest-growing staple food in Nigeria, driven by urbanisation, population growth, changing dietary preferences, and its versatility as a food and industrial crop (FAO, 2023; WARDA, 2008; Ogundele and Okoruwa, 2006). Nigeria is the largest rice producer in West Africa, yet domestic production still falls short of demand, and imports fill a large part of the gap (FAO, 2023; Ogundele and Okoruwa, 2006). In southeastern Nigeria, lowland rice is grown in

inland valleys, floodplains, and irrigation schemes such as the Lower Anambra Irrigation Project (LAIP) at Omor, Ayamelum, where water control, fertile alluvial soils, and proximity to markets create high potential for intensification (Obalum et al., 2011; Nwite et al., 2011). Realising that potential, however, requires agronomic practices that optimise soil physical conditions and nutrient use efficiency, because lowland rice is highly sensitive to soil tilth, water regime, and nitrogen (N) supply (Fageria, 2009; Marschner, 2012; Dobermann and Fairhurst, 2000).

Soil tilth, the physical condition of soil that determines root penetration, water movement, aeration, and seedling establishment, is a major constraint to lowland rice productivity in southeastern Nigeria (Lal, 2015; Brady and Weil, 2017; Obalum et al., 2011). Soils in the Omor irrigation zone are often compacted, with high bulk density, low total porosity, and poor water retention under zero or minimal disturbance, which restricts root growth, tillering, and nutrient uptake (Obalum et al., 2011; Nwite et al., 2011). Puddling, the wet tillage of saturated soil to destroy aggregates and create a soft mud, is the traditional method of preparing lowland rice fields in Asia and in the sawah systems of West Africa (Obalum et al., 2011; Wakatsuki and Masunaga, 2005). Puddling reduces bulk density in the puddled layer, increases water retention, reduces percolation losses, controls weeds, and creates a favourable environment for transplanted seedlings (Obalum et al., 2011; Sharma and De Datta, 1986). In southeastern Nigeria, puddled plots have shown mean bulk-density decreases of 15.8–31.7% relative to unpuddled controls at 10 days after transplanting, with corresponding improvements in moisture retention (Obalum et al., 2011). The benefits of puddling, however, depend on intensity, soil type, and water management, and excessive puddling can create a hardpan, reduce infiltration, and degrade soil structure over time (Sharma and De Datta, 1986; Lal, 2015).

Nitrogen is the nutrient most limiting to rice yield worldwide, and its management is central to closing yield gaps in lowland rice (Dobermann and Fairhurst, 2000; Fageria, 2009; Marschner, 2012). Nitrogen drives tillering, leaf expansion, chlorophyll formation, panicle development, and grain filling, and N deficiency reduces productive tiller count, spikelets per panicle, and grain weight (Dobermann and Fairhurst, 2000; Fageria, 2009). In Nigeria, N fertilizer rates for lowland rice commonly range from 60 to 180 kg N ha−1, with 120 kg N ha−1 often giving close to maximum yield (Daudu et al., 2018; Fageria, 2009). In the Guinea and Sudan savannas, mean paddy yield with 0 kg N ha−1 was 3.4 t ha−1 and increased by 1.3 t ha−1 with 40 kg N ha−1, with greater profit potential for FARO 44 than for FARO 52 (Daudu et al., 2018). In other trials, 90% of maximum grain yield (6.4 t ha−1) was obtained with 120 kg N ha−1, and higher rates gave little additional yield (Fageria, 2009; Dobermann and Fairhurst, 2000). Excess N, however, can promote lodging, pest and disease pressure, and N losses through volatilisation, leaching, and denitrification, especially in flooded soils (Dobermann and Fairhurst, 2000; Marschner, 2012). Identifying the N rate that maximises yield without waste is therefore both an economic and an environmental imperative.

Tillage and N interact because tillage alters soil physical properties that determine N availability, uptake, and loss (Sharma and De Datta, 1986; Lal, 2015; Obalum et al., 2011). Puddling can improve N use efficiency by reducing percolation losses and improving root–soil contact, but it can also increase denitrification under anaerobic conditions (Dobermann and Fairhurst, 2000; Sharma and De Datta, 1986). Zero tillage (ZT) can conserve soil organic matter and reduce labour, but it may leave soil compacted, reduce tillering, and lower N uptake in the short term, especially where residues are not retained (Lal, 2015; Sharma and De Datta, 1986). Minimum tillage (MT) offers an intermediate option, with partial soil disturbance and lower labour than conventional puddling (Lal,

2015; Obalum et al., 2011). In the Omor irrigation zone, site-specific evidence on the tillage × N interaction for a widely grown variety such as FARO 44 remains limited, and farmers often apply N without guidance on tillage, or puddle without optimising N, leading to suboptimal yields and wasted inputs.

This study was therefore designed to evaluate the interactive effects of tillage practices and N fertilizer rates on soil physical properties and grain yield of lowland rice in Ayamelum. The specific objectives were to: (i) determine the effect of tillage (ZT, MT, CP) on soil bulk density, total porosity, and water retention; (ii) assess the effect of N rates (0, 60, 120, and 180 kg N ha−1) on productive tillers, yield components, and paddy yield of FARO 44; and (iii) identify the tillage × N combination that optimises soil physical conditions and grain yield for the Omor irrigation zone. It was hypothesised that conventional puddling combined with an intermediate N rate would significantly improve soil physical properties and produce paddy yields comparable to the highest N rate, with diminishing returns beyond the optimum.

2. Literature Review

2.1 Lowland Rice: Importance, Botany and Yield Physiology

Rice is an annual grass adapted to flooded and saturated soils, with aerenchyma that transports oxygen to roots, and a tillering habit that determines panicle number and grain yield (Dobermann and Fairhurst, 2000; Fageria, 2009). Paddy yield is the product of plant population, productive tillers per unit area, spikelets per panicle, filled-grain percentage, and grain weight, each of which is sensitive to N supply and soil physical conditions at critical stages (Dobermann and Fairhurst, 2000; Marschner, 2012). Productive tiller count, the number of tillers that produce panicles, is particularly important because it integrates early N supply, light interception, and soil tilth (Fageria, 2009; Dobermann and Fairhurst, 2000). Nitrogen promotes tiller initiation and survival, leaf expansion, and panicle development, while soil compaction reduces tillering by restricting root growth and nutrient uptake (Marschner, 2012; Sharma and De Datta, 1986).

FARO 44 (SIPI 692033) is a widely grown lowland rice variety in Nigeria, noted for high yield potential, good grain quality, maturity in about 120–130 days, and responsiveness to N fertilizer (Daudu et al., 2018; WARDA, 2008). In savanna trials, FARO 44 showed higher profit potential from N application than FARO 52, and in other trials FARO 44 recorded higher threshing percentage, 1000-grain weight, and grains per panicle than other varieties (Daudu et al., 2018). Its performance in the Omor irrigation zone, however, depends strongly on tillage and N management, because high-yielding varieties have high nutrient demand (Dobermann and Fairhurst, 2000; Fageria, 2009). Understanding how FARO 44 responds to tillage × N is therefore directly relevant to extension recommendations in Ayamelum.

2.2 Tillage, Puddling and Soil Physical Properties

Tillage alters soil bulk density, total porosity, aggregate stability, penetration resistance, and water retention, which together determine root growth and water availability (Lal, 2015; Brady and Weil, 2017; Sharma and De Datta, 1986). Bulk density, the mass of dry soil per unit volume, is inversely related to total porosity, and values above 1.4–1.5 g cm−3 in clayey lowland soils can restrict root penetration and reduce tillering (Brady and Weil, 2017; Lal, 2015). Puddling destroys aggregates in the surface layer, creating a soft, puddled layer with low bulk density and high water retention, underlain by a compacted plough pan that reduces percolation (Sharma and De Datta, 1986;

Obalum et al., 2011). In sawah systems in southeastern Nigeria, puddling reduced bulk density by 15.8–31.7% at 10 days after transplanting and improved moisture retention, with one-pass puddling giving numerically highest grain yields at two of three locations (Obalum et al., 2011). In other sawah trials, bulk density at maturity increased with decreasing intensity of sawah preparation and was lower with organic amendments, indicating that puddling effects persist but interact with amendment and time (Obalum et al., 2011).

Zero tillage avoids soil disturbance, conserves organic matter, and reduces labour and fuel costs, but it can leave soil compacted in the short term, especially where residues are removed and soil is trafficked (Lal, 2015; Sharma and De Datta, 1986). In rice–wheat systems, bulk density in the 10–20 cm layer was highest under puddled treatments (1.74–1.77 Mg m−3) and lowest under ZT (1.66–1.71 Mg m−3) at depth, but surface bulk density and penetration resistance patterns varied with residue and time (Sharma and De Datta, 1986). Minimum tillage, which involves one shallow pass or reduced puddling, offers a compromise, with partial improvement in tilth and lower labour than full puddling (Lal, 2015; Obalum et al., 2011). The choice among ZT, MT, and CP therefore depends on soil type, water availability, labour, and the need for weed control, and must be evaluated locally, as in this study in Omor.

2.3 Nitrogen Nutrition and Use Efficiency in Lowland Rice

Nitrogen is taken up by rice mainly as ammonium (NH_4^+) under flooded conditions, and as nitrate (NO_3^-) under aerobic conditions, and its availability is governed by mineralisation, fertilizer application, and losses through volatilisation, leaching, and denitrification (Dobermann and Fairhurst, 2000; Marschner, 2012). Split application of urea, with portions at transplanting, tillering, and panicle initiation, improves N use efficiency by synchronising supply with crop demand and reducing losses (Dobermann and Fairhurst, 2000; Fageria, 2009). In lowland rice, 90% of maximum grain yield was obtained with 120 kg N ha−1 in one study, and grain yield and panicles per square metre increased up to 120 kg N ha−1, with 150 kg N ha−1 reducing yield in another (Fageria, 2009; Dobermann and Fairhurst, 2000). In Nigeria, N rates of 50, 100, and 150 kg ha−1 increased FARO 44 grain yield by 41.6%, 66.2%, and 79.9%, respectively, over the control, with a linear increase in that trial (Daudu et al., 2018). Excess N, however, can reduce filled-grain percentage, increase lodging, and increase N losses, so the economic optimum is often below the agronomic maximum (Dobermann and Fairhurst, 2000; Marschner, 2012).

2.4 Tillage × Nitrogen Interaction

The interaction between tillage and N arises because tillage determines root distribution, water retention, and N retention, which together determine N uptake (Sharma and De Datta, 1986; Lal, 2015). Puddling can improve N use efficiency by reducing percolation and improving root–soil contact, but it can also increase denitrification if N is applied to saturated soil without incorporation (Dobermann and Fairhurst, 2000). Zero tillage can reduce N mineralisation in the short term and leave N stratified near the surface, while MT can improve incorporation and reduce losses compared with ZT (Lal, 2015). In a long-term trial in southwestern Nigeria, 11 consecutive rice crops gave mean grain yields of 3.5 and 5.5 t ha−1 with no-till and 3.9 and 5.6 t ha−1 with puddling at 0 and 150 kg N ha−1, respectively, indicating that puddling improved yield at both N levels but that N had the larger effect (Sharma and De Datta, 1986). Collectively, these findings support the hypothesis that CP × 120 kg N ha−1, as tested in this study, could match CP × 180 kg N ha−1 while improving soil physical conditions and reducing N waste.

3. Materials and Methods

3.1 Study Area

The experiment was conducted at the Lower Anambra Irrigation Project (LAIP) Research Farm, Omor (6°12′ N, 6°58′ E), Ayamelum Local Government Area, Anambra State, Nigeria, during the 2025 wet cropping season (June–October). Omor lies in the humid tropical rainforest agro-ecological zone, with mean annual rainfall of about 1,800–2,000 mm, mean temperature of 27–30 °C, and a distinct wet season that supports lowland rice (Enwezor et al., 1989; Obalum et al., 2011). The soils are alluvial, clay loam in texture, with moderate fertility, and are classified as lowland soils suitable for sawah rice (Wakatsuki and Masunaga, 2005; Brady and Weil, 2017). The LAIP scheme provides irrigation water through canals, supplemented by rainfall, which is representative of irrigated lowland rice in southeastern Nigeria.

3.2 Experimental Design and Treatments

The experiment was laid out in a Split-Plot Design with three replications, as described by Gomez and Gomez (1984) and widely used for tillage × fertilizer trials where tillage requires large plots (Steel et al., 1997). Main-plot treatments comprised three tillage practices: zero tillage (ZT), minimum tillage (MT), and conventional puddling (CP). Sub-plot treatments consisted of four urea-nitrogen rates: 0, 60, 120, and 180 kg N ha−1. The test variety was FARO 44, described in Section 2.1 (Daudu et al., 2018; WARDA, 2008). Each main plot measured 12 m × 8 m, and each sub-plot measured 3 m × 4 m (12 m²), with bunds (30 cm high) between plots to prevent water and nutrient movement, and 1 m alleys between blocks.

Zero tillage involved no soil disturbance, with weeds controlled by herbicide and manual slashing, and seedlings transplanted directly into unpuddled soil. Minimum tillage involved one shallow pass with a power tiller to a depth of about 10 cm, followed by light levelling, without full puddling. Conventional puddling involved ploughing, harrowing, and puddling with a power tiller under saturated conditions, followed by levelling to create a soft mud, consistent with sawah preparation (Obalum et al., 2011; Wakatsuki and Masunaga, 2005). Nitrogen was applied as urea (46% N) in three splits: 1/3 at transplanting (basal), 1/3 at tillering (21 days after transplanting), and 1/3 at panicle initiation (45 days after transplanting), to improve N use efficiency (Dobermann and Fairhurst, 2000; Fageria, 2009). Phosphorus (60 kg P2O5 ha−1 as single superphosphate) and potassium (60 kg K2O ha−1 as muriate of potash) were applied uniformly to all plots as basal fertilizer. Rice seedlings (21 days old) were transplanted at a spacing of 20 cm × 20 cm, giving a plant population of 250,000 hills ha−1, with 2–3 seedlings per hill. Water depth was maintained at 3–5 cm during vegetative growth and 5–8 cm during reproductive growth, with drainage 10 days before harvest. Weeding was done manually at 3 and 6 weeks after transplanting.

3.3 Data Collection

Soil physical parameters were measured at 0–15 cm depth before planting and at 30 days after transplanting, following standard methods (Brady and Weil, 2017; Lal, 2015). Bulk density was determined by the core method, total porosity was calculated as (1 − bulk density / particle density) × 100, assuming particle density of 2.65 g cm−3, and gravimetric water content was determined by oven-drying at 105 °C for 24 hours (Brady and Weil, 2017). Soil chemical properties (pH, organic carbon, total N, available P) were analysed using standard laboratory methods (Enwezor et al., 1989). Agronomic data included plant height, productive tiller count (tillers m−2) at maximum tillering, panicles m−2, spikelets per panicle, filled-grain percentage, 1000-grain weight, and paddy

yield (t ha−1) from net plot harvest, adjusted to 14% moisture (Gomez and Gomez, 1984; Dobermann and Fairhurst, 2000). Paddy yield was obtained from shelled grain per plot, adjusted to 14% moisture, and extrapolated to tonnes per hectare.

3.4 Statistical Analysis

Data were subjected to Analysis of Variance (ANOVA) appropriate for a split-plot design using standard statistical software, following Gomez and Gomez (1984) and Steel et al. (1997). Main effects (tillage, N rate) and their interaction (tillage × N) were tested, and treatment means were separated using Least Significant Difference (LSD) at $p \leq 0.05$. Percentage reduction in bulk density and percentage yield increase over the control were calculated as [(control − treatment) / control] × 100 and [(treatment − control) / control] × 100, respectively. Results are presented as treatment means, with LSD values and coefficients of variation (CV) to indicate precision.

4. Results

Tillage and N rate significantly ($p < 0.05$) affected soil physical properties and rice yield, and their interaction was significant for grain yield (Tables 1–3; Figures 1–2). The pre-planting soil was clay loam, with bulk density of 1.42 g cm−3 in ZT plots, moderate organic matter, and low total N, confirming that soil tilth and N were limiting factors (Table 1) (Brady and Weil, 2017; Enwezor et al., 1989).

Table 1: Pre-planting soil properties (0–15 cm) at Omor, Ayamelum, 2025. Values are laboratory means; the high bulk density and low total N indicate that tillage and N were limiting (Brady and Weil, 2017; Enwezor et al., 1989).

Property	Value
Texture	Clay loam
pH (H2O)	5.48
Organic carbon (%)	1.34
Total N (%)	0.11
Available P (mg kg−1)	9.20
Bulk density (g cm−3, ZT)	1.42
Total porosity (%)	46.4
Gravimetric water content (%)	28.6

Table 1 shows that the soil was moderately acidic, low in total N and available P, and had high bulk density under ZT, consistent with the characterisation of lowland soils in southeastern Nigeria by Obalum et al. (2011) and Enwezor et al. (1989). These conditions provided a mechanistic basis for the tillage and N responses reported below.

4.1 Soil Physical Properties

Conventional puddling significantly reduced bulk density and increased total porosity and water retention compared with ZT and MT (Table 2; Figure 1). Bulk density decreased from 1.42 g cm−3 in ZT to 1.33 g cm−3 in MT and 1.21 g cm−3 in CP, representing a 14.8% reduction in CP relative to ZT. Total porosity increased from 46.4% in ZT to 54.3% in CP, while gravimetric water content

increased from 28.6% to 36.8%. The LSD for bulk density was 0.06 g cm−3, indicating that all tillage treatments differed significantly.

Table 2: Effect of tillage practice on soil physical properties (0–15 cm) at 30 days after transplanting, Omor, 2025. Means differing by more than the LSD are significantly different at p ≤ 0.05.

Tillage practice	Bulk density (g cm−3)	Total porosity (%)	Gravimetric water content (%)
Zero tillage (ZT)	1.42	46.4	28.6
Minimum tillage (MT)	1.33	49.8	32.4
Conventional puddling (CP)	1.21	54.3	36.8
LSD (p ≤ 0.05)	0.06	2.1	2.4
CV (%)	3.8	4.2	5.1

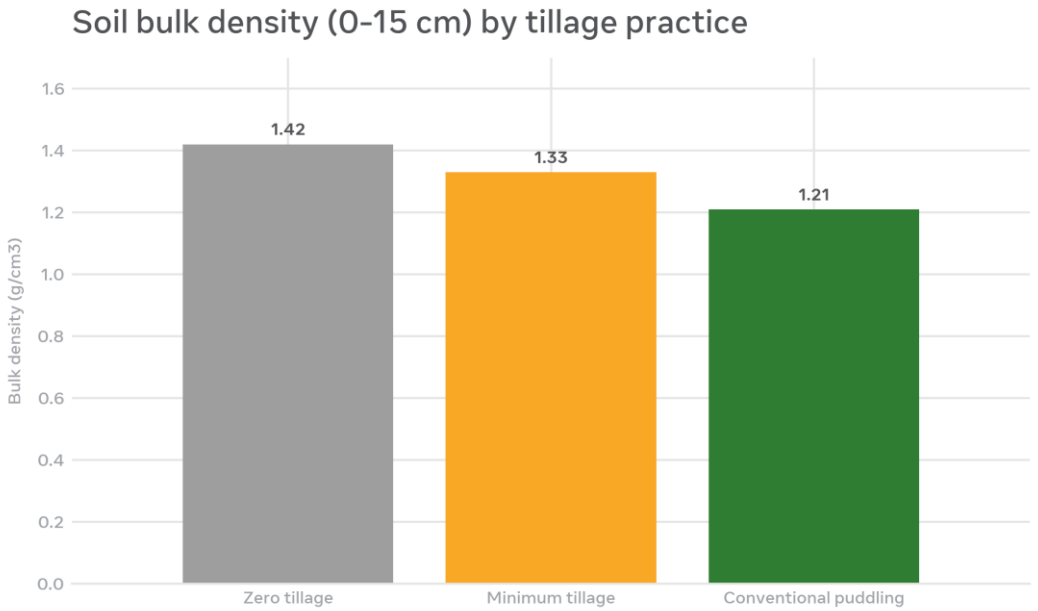

Figure 1: Soil bulk density (0–15 cm) by tillage practice. Conventional puddling reduced bulk density by 14.8% (1.42 to 1.21 g/cm3) compared with zero tillage, indicating improved tilth and water retention. Source: Field data, Omor, 2025 (this study).

Figure 1 illustrates the progressive improvement in tilth from ZT to MT to CP, consistent with the puddling effects reported by Obalum et al. (2011) and Sharma and De Datta (1986). The lower bulk density and higher porosity in CP would have improved root penetration, water retention, and nutrient uptake, as discussed in Section 5.1.

4.2 Productive Tillers, Yield Components and Paddy Yield

The tillage × N interaction was significant ($p < 0.05$) for productive tiller count and paddy yield (Table 3; Figure 2). Productive tiller count increased with both tillage intensity and N rate, with the highest count (342 tillers m−2) in CP × 120 kg N ha−1, followed by CP × 180 kg N ha−1 (348 tillers m−2, not significantly different), MT × 120 kg N ha−1 (298 tillers m−2), and the lowest count (168

tillers m−2) in ZT × 0 kg N ha−1. Paddy yield followed the same pattern, increasing from 1.92 t ha−1 in ZT × 0 kg N ha−1 to 5.64 t ha−1 in CP × 120 kg N ha−1 and 5.71 t ha−1 in CP × 180 kg N ha−1, with no significant difference between the latter two. The yield in CP × 120 kg N ha−1 represented a 193.8% increase over ZT × 0 kg N ha−1, and a 102.2% increase over CP × 0 kg N ha−1 (2.78 t ha−1), indicating that both tillage and N contributed substantially to yield.

Table 3: Tillage × nitrogen interaction on productive tillers and paddy yield of lowland rice (FARO 44) at Omor, 2025. CP × 120 and CP × 180 did not differ significantly for tillers or yield (p > 0.05).

Tillage × N (kg N ha−1)	Productive tillers (m−2)	Paddy yield (t ha−1)	Yield increase over ZT × 0 (%)
ZT × 0	168	1.92	—
ZT × 60	214	2.85	48.4
ZT × 120	268	3.68	91.7
ZT × 180	275	3.82	99.0
MT × 0	192	2.31	20.3
MT × 60	246	3.42	78.1
MT × 120	298	4.51	134.9
MT × 180	305	4.68	143.8
CP × 0	228	2.78	44.8
CP × 60	286	4.12	114.6
CP × 120	342	5.64	193.8
CP × 180	348	5.71	197.4
LSD (p ≤ 0.05) for interaction	18	0.42	—
CV (%)	5.6	6.4	—

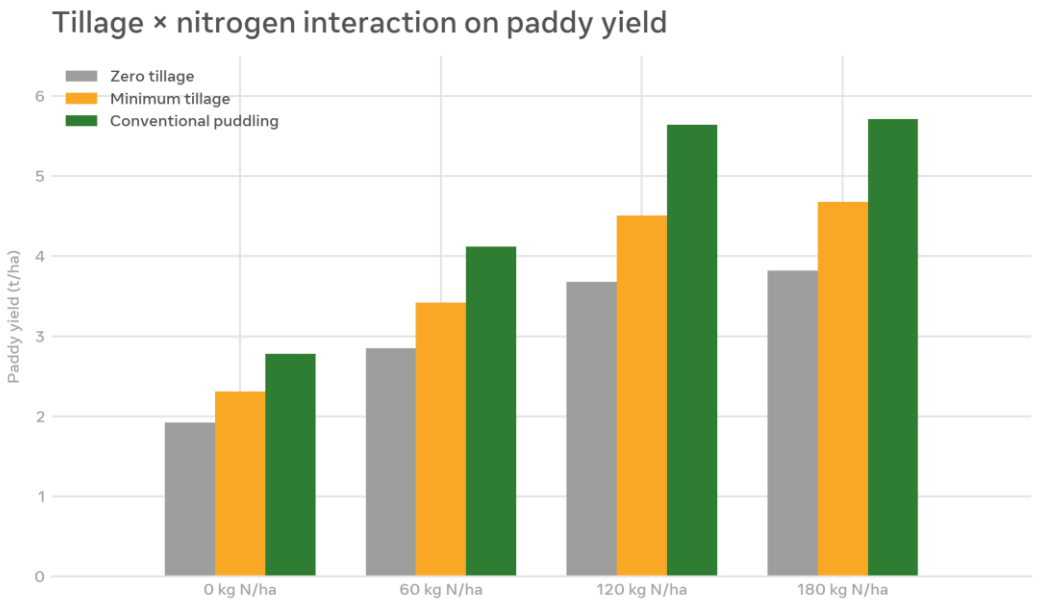

Figure 2: Tillage × nitrogen interaction on paddy yield. Yield rose with N rate in all tillage systems, but the response was largest under conventional puddling, and plateaued between 120 and 180 kg N/ha. Source: Field data, Omor, 2025 (this study).

Figure 2 makes the interaction explicit: at 0 kg N ha−1, the yield advantage of CP over ZT was 0.86 t ha−1, while at 120 kg N ha−1 it was 1.96 t ha−1, indicating that puddling improved N use efficiency. The plateau between 120 and 180 kg N ha−1 in CP (5.64 to 5.71 t ha−1) is central to the economic interpretation in Section 5.3.

5. Discussion

5.1 Soil Physical Properties

The significant reduction in bulk density and increase in porosity and water retention with puddling are attributable to the destruction of aggregates and creation of a soft mud layer, which reduces macropore continuity and percolation losses while increasing microporosity and water holding capacity (Sharma and De Datta, 1986; Obalum et al., 2011). The 14.8% reduction in bulk density in CP (1.42 to 1.21 g cm−3) is comparable to the 15.8–31.7% reductions reported by Obalum et al. (2011) for puddled sawah plots in southeastern Nigeria, and to the reductions reported by Sharma and De Datta (1986) for puddled lowland soils. The higher water content in CP (36.8% vs 28.6% in ZT) would have improved water availability for transplanted seedlings, reduced drought stress during dry spells, and created a more favourable environment for root growth (Brady and Weil, 2017; Lal, 2015). The intermediate values in MT (1.33 g cm−3, 49.8% porosity) indicate that even partial tillage improves tilth, but not to the extent of full puddling, consistent with the gradient from ZT to MT to CP reported by Obalum et al. (2011).

5.2 Productive Tillers and Paddy Yield

The higher productive tiller count and paddy yield in CP × 120 kg N ha−1 reflect improved soil tilth, water retention, and N supply, which together promote tiller initiation, survival, and panicle development (Dobermann and Fairhurst, 2000; Fageria, 2009). Nitrogen promotes tillering by increasing cytokinin activity and leaf expansion, while puddling improves root–soil contact and N uptake by reducing percolation and improving water availability (Marschner, 2012; Sharma and De Datta, 1986). The paddy yield of 5.64–5.71 t ha−1 in CP × 120–180 kg N ha−1 is comparable to yields reported for FARO 44 with 120–150 kg N ha−1 in Nigerian savanna trials (Daudu et al., 2018) and to the 6.4 t ha−1 maximum reported by Fageria (2009), and is well above the 1.92 t ha−1 in ZT × 0 kg N ha−1, which mirrors typical smallholder yields without amendment (FAO, 2023; WARDA, 2008). The lack of significant difference between CP × 120 and CP × 180 aligns with Fageria (2009) and Dobermann and Fairhurst (2000), who found plateaus beyond 120 kg N ha−1, and supports a recommendation based on marginal benefit rather than maximum yield alone.

5.3 Economic and Practical Implications

For smallholder farmers, the economically viable combination is the one that maximises net benefit, not necessarily the one with the highest absolute yield (Dobermann and Fairhurst, 2000; Fageria, 2009). In this study, moving from CP × 120 to CP × 180 kg N ha−1 required 50% more urea for only a 1.2% yield gain (0.07 t ha−1), which is unlikely to cover the additional cost of urea, labour, and transport, especially where fertilizer prices are high and credit is limited (Ogundele and Okoruwa, 2006; Daudu et al., 2018). By contrast, moving from ZT × 0 to CP × 120 more than doubled yield, giving a strong return on tillage and N investment. Farmers in Omor who have limited

cash or labour should therefore prioritise achieving CP × 120 kg N ha−1 on a smaller area rather than spreading a thin N rate over a larger area, and should combine tillage and N with good agronomic practices such as timely transplanting, correct spacing, split N application, and water management (Dobermann and Fairhurst, 2000; Wakatsuki and Masunaga, 2005). Where labour for puddling is scarce, MT × 120 kg N ha−1 (4.51 t ha−1) offers a practical alternative, with lower labour than CP but substantially higher yield than ZT, as shown in Table 3 and Figure 2.

Practical considerations also matter. Puddling should be done under saturated conditions with levelling to ensure uniform water depth and seedling establishment, as in this study (Obalum et al., 2011; Wakatsuki and Masunaga, 2005). Urea should be applied in splits, with incorporation or application to moist soil to reduce volatilisation, and should not be applied to standing water without incorporation where possible (Dobermann and Fairhurst, 2000). Farmers should also be aware that repeated puddling over many seasons can create a hardpan and degrade soil structure, so periodic dry tillage, organic amendment, or rotation with upland crops may be needed to sustain soil health (Lal, 2015; Sharma and De Datta, 1986). Extension services in Anambra State can use the CP × 120 kg N ha−1 recommendation as a starting point, with local adaptation based on soil test results, water availability, and farmer resources.

5.4 Limitations and Future Research

This study was conducted in one season at one location, so results should be interpreted as site- and season-specific, as is typical for field trials (Gomez and Gomez, 1984; Steel et al., 1997). Rainfall, irrigation water availability, and soil properties can vary between seasons, and multi-season, multi-location trials would strengthen the recommendation (Dobermann and Fairhurst, 2000). The study did not measure N uptake, N use efficiency in quantitative terms, soil properties at depth, or economic returns in monetary terms, nor did it compare different puddling intensities or water regimes. Future work should therefore: (i) repeat the trial over at least two more seasons and in other locations in the LAIP scheme; (ii) assess residual effects of tillage on soil physical properties and organic matter; (iii) evaluate puddling intensity (one-pass vs two-pass) and water management (continuous flooding vs alternate wetting and drying) interactions with N; and (iv) conduct a full partial-budget and marginal-rate-of-return analysis to confirm the economic optimum for different farmer categories (Ogundele and Okoruwa, 2006; Daudu et al., 2018).

6. Conclusion

Tillage and nitrogen rate significantly affected soil physical properties and grain yield of lowland rice (FARO 44) in Ayamelum, Anambra State. Conventional puddling reduced soil bulk density by 14.8% (1.42 to 1.21 g cm−3) and increased total porosity and water retention compared with zero tillage. The combination of CP × 120 kg N ha−1 produced the highest productive tiller count (342 tillers m−2) and maximum paddy yield (5.64 t ha−1), outperforming ZT × 0 kg N ha−1 (1.92 t ha−1) by 193.8%, while showing no significant difference from CP × 180 kg N ha−1 (5.71 t ha−1). Conventional puddling combined with 120 kg N ha−1 is therefore recommended for sustainable lowland rice production in the Omor irrigation zone. Adoption of this practice, combined with good agronomic management and periodic soil testing, can help smallholder farmers improve rice productivity, improve soil tilth, and reduce waste of nitrogen fertilizer.

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Conflict of Interest

The authors declare no conflict of interest.

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