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Evaluation of the Impact of Herbicides on Soil Characteristics and Grain Yield of Transplanted Rainfed and Irrigated Rice Farming Systems in Makurdi Benue State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author API designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors JAA and AE managed the analyses of the study. Author AE managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Herbicides play a vital role in rice production by managing weed growth that competes with crops for essential resources such as nutrients, water, and light. Understanding how herbicide application influences soil properties and rice productivity in these systems is crucial for sustainable agriculture

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and informed management decisions aimed at boosting rice yield while conserving soil health. This study evaluated the impact of integrated pre- and post-emergence herbicide applications on soil physicochemical properties and grain yield in transplanted rainfed and irrigated rice farming systems in Makurdi, Benue State, Nigeria. The experiment was conducted during the 2024 cropping season using a randomised complete block design with eight treatments, including controls, manual weeding, and combinations of pendimethalin, Solito 320 EC, and Patriarc herbicides at varying rates. Soil samples and yield data were collected from plots under both rainfed (wet season) and irrigated (dry season) conditions. Data were subjected to analysis of variance (ANOVA) using Genstat Release 3.1 and R statistical software. Results showed herbicide treatments significantly influenced soil texture, bulk density, porosity, water holding capacity, and chemical properties such as pH, organic carbon, total nitrogen, and exchangeable bases. High herbicide rates generally reduced organic carbon and nutrient availability, while moderate applications and manual weeding improved soil porosity and aggregation. Irrigated soils exhibited lower bulk density and higher nutrient contents compared to rainfed soils, consistent with enhanced moisture regimes supporting better soil conditions. Grain yield was significantly higher in plots treated with combined herbicides, exceeding 6 t/ha, compared to controls (~0.5 t/ha) and manual weeding (~4.5 t/ha), indicating effective weed control enhanced productivity in both systems. Correlation analyses highlighted contrasting soil compaction effects under irrigation versus rainfed environments, emphasising the need to balance herbicide use to preserve soil health while maximising yield. This study underscores the importance of optimising herbicide regimes tailored to local soil and water management conditions to sustain rice production and soil fertility in tropical agro-ecosystems like Makurdi.

Keywords: Herbicides; soil properties; grain yield; transplanted rice; rainfed; irrigated.

1. INTRODUCTION

Herbicides play a crucial role in modern agriculture by controlling weeds and ensuring sustainable crop productivity. However, the use of herbicides has raised concerns regarding their contamination, posing a serious threat to the environment, biodiversity, and food safety (Parven *et al*., 2025). It also play a vital role in rice production by managing weed growth that competes with crops for essential resources such as nutrients, water, and light. In transplanted rainfed and irrigated rice systems, herbicides contribute significantly to yield stability and efficiency, but their effects on soil characteristics and grain yield require detailed evaluation, especially within local contexts like Makurdi, Benue State, Nigeria. Understanding how herbicide application influences soil properties and rice productivity in these systems is crucial for sustainable agriculture and informed management decisions aimed at boosting rice yield while conserving soil health.

Rice cultivation globally faces challenges related to weed infestation, which can reduce grain yield substantially if not properly managed. Herbicides, including pre-emergence and post-emergence chemicals, are widely applied to address this issue; however, their interactions with soil attributes vary based on the farming system, environmental conditions, and herbicide formulation. The main chemical agents, known as herbicides, usually target numerous weed species, each of which has varied degrees of efficiency. In agriculturally advanced nations, herbicides are extensively used to effectively manage weed populations and maintain sustainable agricultural practices (Pervaiz *et al*., 2024; Jin *et al*., 2022). Research shows that herbicides can alter soil physicochemical properties, such as pH, organic carbon, nutrient content, and microbial populations, which in turn impact the soil's capacity to support healthy crop growth (Singh et al., 2024). Differences in water management between rainfed and irrigated rice systems further complicate these interactions as soil moisture influences herbicide behaviour and soil microbial activity.

In Makurdi, rainfed rice farming depends exclusively on seasonal rainfall, exposing soils to intermittent wetting and drying cycles. In contrast, irrigated rice fields are subject to continuous water availability controlled through irrigation systems. These divergent moisture regimes lead to distinct soil physical and chemical conditions that potentially influence how herbicides affect soil properties and consequent grain yield outcomes. For instance, irrigated systems often maintain higher soil moisture, which can enhance herbicide mobility and degradation but may also alter the soil microbial community differently compared to rainfed systems (Jiang et al., 2017). Therefore, evaluating the differential impact of herbicides in these two systems is critical to optimising their use for maximum productivity and minimal environmental degradation.

Herbicide efficacy is also closely linked to improvements in rice yield components such as panicle number, grain weight, and overall grain yield. Studies in similar agro-ecological zones have demonstrated that appropriate herbicide application can increase rice grain yield by reducing weed competition, with some herbicide combinations showing yield improvements exceeding 300% over untreated fields (Zhang et al., 2002). Despite these benefits, repeated and improper herbicide use can reduce soil fertility by negatively impacting beneficial soil microbes, organic matter content, and nutrient availability, threatening long-term sustainability. Consequently, the interplay between herbicide effects on soil properties and rice yield needs a comprehensive assessment tailored to the Makurdi environment.

This study's primary objective is to evaluate the impact of herbicides on soil characteristics and grain yield in transplanted rainfed and irrigated rice farming systems in Makurdi, Benue State, Nigeria. The objectives of the study are to: (1) assess the influence of herbicides on essential soil physicochemical properties in rainfed and irrigated rice fields; and (2) determine the effects of herbicide treatment on rice grain yield in both farming systems.

2. METHODOLOGY

The study was conducted during the 2024 cropping season at the Teaching and Research Farms of Joseph Sarwuan Tarka University, Makurdi, Nigeria (7°43′50″N, 8°32′10″E), situated in the Southern Guinea Savannah agro-ecological zone. The site features Typic Ultisols soil, gentle slopes (~3%), and an elevation of 96.3 m above sea level. Makurdi experiences a tropical climate with distinct wet (April–October) and dry (November–March) seasons influenced by southwest maritime and northeast Harmattan winds, respectively. Average annual rainfall is about 1250 mm, mainly between June and September, providing approximately 210 rainy days annually. Temperatures range from 29–38 °C (max) and 15–26 °C (min), with relative humidity varying seasonally between 38–86%. (Gani et al., 2022).

2.1 Experimental Treatments and Design

The experiment employed an integrated herbicide treatment scheme combining pre-emergence application of pendimethalin (Pe) with varying rates of the post-emergence herbicides Patriarc (Pa) and Solito 320 EC (So). Treatments included: - Control (No application), Hand Weeding, So (0.75 L/Ha) + Pe (1.5 L/Ha), So (1.5 L/Ha) + Pe (1.5 L/Ha), So (2.25 L/Ha) + Pe (1.5 L/Ha), Pa (0.15 L/Ha) + Pe (1.5 L/Ha), Pa (0.30 L/Ha) + Pe (1.5 L/Ha) and Pa (0.45 L/Ha) + Pe (1.5 L/Ha).

The treatments were arranged in a Randomised Complete Block Design (RCBD) with three replicates per treatment under both irrigated (dry season) and rainfed (wet season) conditions. Each experimental plot measured 5 m by 4 m, separated by 2 m alleyways between blocks and 1 m between replicates. Rice seeds were procured from the National Cereals Research Institute (NCRI), Badeggi, and herbicides were sourced from SYNGENTA.

2.2 Agronomic Practices

- **Land Preparation:** The experimental fields were cleared of vegetation, ploughed to a depth of 15–20 cm using tractor-drawn implements, and levelled manually to ensure uniform topography and proper water management. Plot boundaries were demarcated with measuring tools, and bunds were constructed to regulate water flow and prevent waterlogging.
- **Nursery Preparation:** Seedlings were raised in 2 m × 2 m nursery plots near the experimental sites. Two kilograms of seed were treated with Apron Star (1 g metalaxy to 3 kg seed) to prevent seed pests. Seeds were planted during the second week of July (rainfed) and the first week of November (irrigated). Watering was

done daily for four weeks before transplanting.

- **Herbicide Application:** Pre-emergence pendimethalin was applied immediately prior to transplanting, while post-emergence Patriarc and Solito were applied two weeks after transplanting, using a calibrated 3-L hand sprayer.
- **Weeding and Control:** Manual weeding was performed at 0, 4, 8, and 12 weeks after sowing on designated plots. Control plots received no herbicide or manual weeding.
- **Fertiliser Application:** Recommended rates of NPK (20:10:10) fertiliser were uniformly broadcast at three weeks after transplanting at 100 kg N/ha, 75 kg P_2O_5/ha, and 50 kg K_2O/ha (Yin et al., 2019).
- **Harvesting:** Manual harvesting was done at physiological maturity by cutting tillers approximately 10 cm above ground level when panicles hardened and browned.

2.3 Soil Sampling and Laboratory Analysis

Composite soil samples (0–15 cm depth) were collected pre-planting and post-harvest for both seasons, totalling 48 composite samples. Key analyses included particle size distribution (hydrometer method), pH and electrical conductivity (soil-water suspension method), organic carbon (Walkley-Black), total nitrogen (Kjeldahl), available phosphorus (Olsen), sulfur (turbidimetric), exchangeable bases (atomic absorption and flame photometry), exchangeable acidity, cation exchange capacity, and base. Soil cores were also taken for physical property analysis, including bulk density, hydraulic conductivity, porosity, and available water content. Samples were air-dried, sieved, and analysed at the Advanced Analytical Soil Science Laboratory, Joseph Sarwuan Tarka University using standard protocols (Gee and Bauder, 1986).

2.4 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using Genstat Release 3.1 and R statistical software. Significant treatment effects were separated using Least Significant Difference (LSD) tests. Regression and correlation analyses were performed between selected soil properties and yield. A t-test compared rice performance across rainfed and irrigated systems.

3. RESULTS AND DISCUSSION

3.1 Soil Properties of the Study Site

The physical and chemical properties of soil at the study site at the experiment's inception in 2024 showed a sandy clay loam texture, characterised by 74% sand, 5.4% silt, and 20.6% clay in the top 0–30 cm layer (Table 1). The soil bulk density was measured at 1.72 Mg m−3−3, with a porosity of 35%, available water content of 23.8 g/m33, and hydraulic conductivity (Ksat) of 10.20, reflecting moderate permeability. The soil pH was mildly acidic at 6.5, with organic matter at 4.3%, total nitrogen at 0.35%, and available phosphorus at 4.88 mg/kg. Exchangeable bases such as potassium, sodium, magnesium, and calcium were 0.19, 0.07, 0.92, and 1.60 cmol/kg, respectively. Exchangeable acidity and base saturation were 0.83 cmol/kg and 77%, respectively, and the cation exchange capacity (CEC) was moderate at 3.61 cmol/kg. These initial values indicate a soil with moderate fertility but with potential to respond positively to fertilisation (Brady & Weil, 2016).

The weather during the crop growing periods displayed significant differences across seasons (Table 2). The first season (July to October 2024) experienced maximum temperatures ranging between 26.3–30.1 °C and minimum temperatures between 18.7–22.3 °C, with substantial rainfall peaking at 2,948 mm in July. The subsequent season (November 2024 to February 2025) recorded higher maximum temperatures of 29.6–33.8 °C and lower minimum temperatures of 15.4–19.7 °C, but no rainfall occurred, necessitating full irrigation. These climatic conditions directly influence soil moisture dynamics and, consequently, nutrient availability and crop growth (FAO, 2017).

3.2 Effect of Different Integrated Rates of Pre- and Post-Emergence Herbicides on Physical and Chemical Properties of Soils

The effects of varied integrated rates of pre- and post-emergence herbicides on soil physical and chemical properties under both irrigation and rainfed conditions are presented in Tables 2 and 3, respectively. Physical analyses revealed that sand content was higher in treatments involving Solito at 2.25 L/ha (81.67%) and hand weeding, in contrast to lower values under control and Patriarc treatments. Clay content decreased correspondingly, while silt content remained statistically constant, emphasising the selective impact of treatments on soil particle distribution. Bulk density was found to be lower under irrigation (1.57–1.70 g/cm33) compared to rainfed plots (1.64–1.76 g/cm33), consistent with enhanced soil moisture promoting better aggregation and reduced compaction (Salem et al., 2015). Similarly, porosity increased with moderate herbicide applications and manual weeding, reaching maximum values in Patriarc 0.15 L/ha + Pendimethalin 1.5 L/ha treatments. Water holding capacity and hydraulic conductivity showed significant treatment effects, with higher bulk densities and lower conductivities noted under higher herbicide rates, indicating soil structure impairment likely linked to herbicide-induced binding of soil particles or microbial activity reduction.

Chemically, soil pH showed a decrease under higher herbicide rates, with the control displaying more neutral pH values, reflecting potential acidification linked to intensive chemical inputs. Organic carbon and total nitrogen were highest in control plots, declining with increasing herbicide application—especially at 0.45 L/ha of Patriarc combined with 1.5 L/ha Pendimethalin—indicating detrimental effects on soil organic matter and nutrient cycling (Singh & Ghoshal, 2013). Available phosphorus remained statistically unchanged across treatments but showed a slight reduction under elevated herbicide applications, possibly due to altered microbial activity affecting phosphorus mineralisation. Base saturation and exchangeable cations (Ca, Mg, K, Na) mirrored this trend, with control plots maintaining higher concentrations than treated soils, hinting at the negative impact of excessive herbicide use on essential nutrient retention (Das et al., 2012).

The differences between irrigated and rainfed systems were also significant. Irrigated soils demonstrated lower bulk density and higher pH compared to rainfed soils, consistent with improved moisture regimes fostering microbial processes that enhance aggregation and nutrient availability (Majumdar et al., 2023). Nitrogen and potassium contents were elevated under irrigation, likely due to reduced leaching and enhanced mineralisation processes. However, parameters such as porosity, water holding capacity, organic carbon, phosphorus, and grain yield did not differ significantly between water management systems, suggesting that intrinsic soil properties and crop genetics also strongly influence these factors (Pascual & Wang, 2016).

Rice grain yield (Table 4) responded markedly to herbicide treatments with superior performance in plots receiving combined herbicide applications (Patriarc + Pendimethalin and Solito + Pendimethalin) in both irrigation scenarios. Yields under these treatments reached over 6 t/ha, significantly higher than the control (0.52–0.57 t/ha) and even surpassing hand weeding (around 4.5 t/ha). This aligns with findings by Chauhan et al. (2015), where integrated chemical weed control optimised canopy development and resource capture, enhancing photosynthesis and yield components. Correlation analyses (Tables 5, 6, 7) revealed that in irrigated conditions, high bulk density negatively correlated with porosity, nutrient levels, and yield, indicating soil compaction restricts root penetration and nutrient uptake despite adequate moisture. In contrast, rainfed conditions showed positive correlations, suggesting that moderate compaction may promote soil aggregation and moisture retention advantageous under variable rainfall (Javaid & Ali, 2022).

The distinct impacts of herbicide rates on soil properties elucidate the balance needed for sustainable weed management. Moderate rates preserving microbial integrity can improve soil structure and fertility, while excessive use exacerbates compaction, reduces soil biochemical activity, and lowers nutrient availability, impeding crop performance (Adeux et al., 2019). Overall, managing soil physical and chemical health under differing irrigation regimes with integrated herbicide applications is crucial for optimising rice production and sustaining soil quality in tropical agricultural systems.

Table 1. Physical and Chemical Properties of the Soil of the Study Site at the Start of the Experiment

Soil Properties	Value
Sand (%)	74
Silt (%)	5.4
Clay (%)	20.6
Textural Class	SCL
Soil pH	6.50
Electrical Conductivity (dSm^{-1})	0.05
Organic Carbon (gkg^{-1})	2.50
Organic Matter	4.30
Total nitrogen (gkg^{-1})	0.37
Available Phosphorus (mg/kg)	4.88
Exchangeable bases (cmol/kg):	
K	0.19
Na	0.07
Ca	1.60
Mg	0.92
$AL^{2+}+H^{+}$ (cmol/kg)	0.83
ECEC (cmol/kg)	3.61
Base Saturation (%)	77
Bulk Density (Mgm-3)	1.72
Porosity (%)	35
AW (gm-3)	23.8
HC (Ksat)	10.20

Key: SCL = Sandy Clay Loam, HC = Hydraulic Conductivity, AW = Available Water

Table 2. Effect of different integrated rates of pre- and post-emergence herbicides on soil physical properties

Soil physical properties								
Irrigated								
Treatment	**Sand**	**Silt**	**Clay**	**Bulk Density**	**Particle Density**	**Porosity**	**Water Holding Capacity**	**Hydraulic Conductivity**
Control (No application)	78.33a	5.4a	16.57d	1.58ab	2.57b	39.07c	10.04d	0.1
Hand Weeding	81.33de	5.4a	13.27ab	1.59b	2.467a	35.85a	10.06e	0.08
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	79.67abc	5.4a	14.27bc	1.67e	2.76d	41.23e	11.92f	0.04
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	81.00bcd	5.4a	13.57abc	1.69f	2.8e	39.18c	9.82c	0.04
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	78.67ab	5.067a	16.27d	1.7f	2.663c	36.4b	15.16h	0.03
So (0.75 L/Ha) + Pe(1.5 L/Ha)	80.67cde	5.4a	13.93abc	1.57a	2.667c	39.47c	14.25g	0.08
So (1.5 L/Ha) + Pe(1.5 L/Ha)	80.00bcd	5.4a	14.6c	1.61c	2.673d	39.42c	9.53b	0.07
So (2.25 L/Ha) + Pe(1.5 L/Ha)	81.67e	5.4a	12.93a	1.64d	2.753d	40.38d	9.5a	0.06
Rainfed								
Control (No application)	78.33a	5.4a	16.57d	1.653ab	2.633b	38.06c	9.95c	0.1
Hand Weeding	81.33de	5.4a	13.27ab	1.67bc	2.547a	35.35a	10.02d	0.08
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	79.67abc	5.4a	14.27bc	1.743de	2.78e	39.41d	11.87e	0.04
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	81cde	5.4a	13.57abc	1.727d	2.8e	39.15d	9.77b	0.04
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	78.67ab	5.067a	16.27d	1.75de	2.663c	36.35b	15.11g	0.03
So (0.75 L/Ha) + Pe(1.5 L/Ha)	80.67cde	5.4a	13.93abc	1.64a	2.733d	41.18f	14.22f	0.08
So (1.5 L/Ha) + Pe(1.5 L/Ha)	80bcd	5.4a	14.6c	1.687c	2.73b	39.37d	9.48a	0.07
So (2.25 L/Ha) + Pe(1.5 L/Ha)	81.67e	5.4a	12.93a	1.763e	2.773e	40.33e	9.45a	0.06

Table 3. The Effect of Different Integrated Rates of Pre- and Post-Emergence Herbicides on Soil Chemical Properties

Irrigated										
Treatment	**pH**	**OC**	**OM**	**N**	**AP**	**BS**	**Ca**	**Mg**	**K**	**Na**
Control (No application)	6.633d	2.633d	4.427ab	0.3733c	5.023a	79.67c	1.61d	1.2333d	0.26c	0.17333c
Hand Weeding	6.4b	2.453bc	4.22ab	0.3267bc	4.723a	75.33bc	1.383c	1.1767cd	0.2133b	0.12b
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	6.533cd	2.5c	4.697b	0.2867ab	4.263a	71.67ab	1.36c	0.7767ab	0.18a	0.07667a
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	6.433bc	2.5c	4.483ab	0.2467a	4.323a	69a	1.317b	0.9567abcd	0.16a	0.07a
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	6.267a	2.41abc	4.383ab	0.2267a	4.183a	67.33a	1.273a	0.6667a	0.1567a	0.06667a
So (0.75 L/Ha) + Pe(1.5 L/Ha)	6.367ab	2.333ab	4.017a	0.2567ab	4.29a	72ab	1.36c	1.0933bcd	0.18a	0.07667a
So (1.5 L/Ha) + Pe(1.5 L/Ha)	6.333ab	2.283a	4.443ab	0.2467a	4.323a	70.67ab	1.317b	0.9567abcd	0.16a	0.07a
So (2.25 L/Ha) + Pe(1.5 L/Ha)	6.267a	2.3a	4.3ab	0.24a	4.207a	67.33a	1.273a	0.8333abc	0.1567a	0.06667a
Rainfed										
Control (No application)	6.333e	2.573e	4.377ab	0.3267b	4.983c	76.33c	1.59d	1.2333d	0.26c	0.15333c
Hand Weeding	6.1bcd	2.403cd	4.173ab	0.2933b	4.69b	73.67bc	1.363c	1.1767cd	0.2133b	0.11b
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	6.233de	2.45d	4.647b	0.22a	4.213a	69.67ab	1.34c	0.7767ab	0.18a	0.07a
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	6.133cd	2.45d	4.433ab	0.2a	4.273a	67a	1.297b	0.9567abcd	0.16a	0.07a
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	5.967ab	2.363bcd	4.333ab	0.199a	4.133a	66.67a	1.253a	0.6667a	0.1567a	0.06667a
So (0.75 L/Ha) + Pe(1.5 L/Ha)	6.067abc	2.283abc	3.97a	0.2133a	4.24a	70ab	1.34c	1.0933bcd	0.18a	0.07a
So (1.5 L/Ha) + Pe(1.5 L/Ha)	6.067abc	2.233a	4.393ab	0.2033a	4.273a	68.33a	1.297b	0.9567abcd	0.16a	0.07a
So (2.25 L/Ha) + Pe(1.5 L/Ha)	5.933a	2.25ab	4.25ab	0.21a	4.16a	66a	1.253a	0.8333abc	0.1567a	0.06333a

Table 4. Effect of different integrated rates of pre- and post-emergence herbicides on Grain Yield of Maize

	Grain yield (t/ha)	Panicle Number	Panicle weight (g)	Plant Height(cm)	PLT DM	Number of Tillers	Panicle length (cm)	1000 seed weight(g)	Number of Grains per panicle	Leaf Area index	NU	NFG	Days to 50% Maturity	D5H	D5B
Irrigated															
Control (No application)	0.57a	194.7a	2.583a	58a	2.02a	45a	14.45a	154a	31.33a	0.65a	35e	109a	86c	72a	65.33a
Hand Weeding	4.5b	313b	2.73ab	62a	3.93bc	57b	18.69b	163ab	37.67b	0.7b	25b	121bc	86c	72a	64.67a
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	5.647bc	314b	2.8abc	66a	3.43bc	64cd	20.11d	167abc	40.67bc	0.7b	25b	121bc	85bc	71.33a	63.33a
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	6.22c	331b	2.95abc	68a	3.96bc	68cde	20.17d	175bc	46de	0.73bc	22a	130e	83a	70.67a	63a
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	6.3c	337b	3.21c	69a	4.21c	71e	22.16e	180c	47e	0.77d	21a	127d	84ab	70a	63a
So (0.75 L/Ha) + Pe(1.5 L/Ha)	5.573bc	310b	2.78abc	64a	2.8ab	63c	20.09d	165abc	40bc	0.7b	28d	121bc	85bc	71a	63.33a
So (1.5 L/Ha) + Pe(1.5 L/Ha)	6.207c	320b	2.84abc	65a	3.23abc	67cde	19.19c	170bc	43cd	0.71bc	27cd	122c	83a	70.67a	63.67a
So (2.25 L/Ha) + Pe(1.5 L/Ha)	6.36c	327b	3.11bc	68a	3.263abc	70de	22.06e	178bc	46de	0.74cd	26bc	120b	83.67ab	70.67a	63.33a
Rainfed															
Control (No application)	0.52a	14.4a	2.533a	56a	2a	41.67a	150a	191.3a	30a	0.6367a	35e	109a	88c	74a	67a
Hand Weeding	4.45b	18.64b	2.68ab	60ab	3.91bc	55b	160ab	309b	35.67b	0.69b	25b	121bc	88c	74a	66a
Pa (0.15 L/Ha) + Pe(1.5 L/Ha)	5.597b	20.09d	2.75abc	64ab	3.41bc	62cd	162.3ab	310.3b	37.67bc	0.6867b	25b	121bc	87bc	73a	65a
Pa (0.30 L/Ha) + Pe (1.5 L/Ha)	6.02b	20.12d	2.9abc	66ab	3.95bc	66cde	170b	326b	44de	0.7133bc	22a	130e	86ab	72a	65a
Pa (0.45 L/Ha) + Pe (1.5 L/Ha)	6.1b	22.12e	3.16c	67.67ab	4.19c	69e	175b	332b	45e	0.74c	21a	127d	85a	71.33a	65a
So (0.75 L/Ha) + Pe(1.5 L/Ha)	5.373b	20.03d	2.73abc	61.67ab	2.78ab	61c	162ab	305b	38bc	0.6833b	28d	121bc	87bc	73a	65a
So (1.5 L/Ha) + Pe(1.5 L/Ha)	6.153b	19.14c	2.757abc	66ab	3.21abc	65cde	165ab	316.7b	41cd	0.7067bc	27cd	122c	85a	72a	66a
So (2.25 L/Ha) + Pe(1.5 L/Ha)	6.16b	22.01e	3.06bc	66.33ab	3.247abc	68de	173b	323.7b	44de	0.73c	26bc	120b	85.67ab	72a	65a

Table 5. Correlation of Rice Yield and Soil Properties Under Irrigated Rice System

		Bulk density	Porosity	Water Holding Capacity	Ph	Organic carbon	Nitrogen	Available Phosphorus	Potassium	Grain yield (t/ha)
Bulk density	Pearson Correlation	1								
	Sig. (2-tailed)									
	N	24								
Porosity	Pearson Correlation	-.926**	1							
	Sig. (2-tailed)	.000								
	N	24	24							
Water holding capacity	Pearson Correlation	-.848**	.774**	1						
	Sig. (2-tailed)	.000	.000							
	N	24	24	24						
pH	Pearson Correlation	.012	-.011	-.059	1					
	Sig. (2-tailed)	.954	.961	.785						
	N	24	24	24	24					
Organic carbon	Pearson Correlation	-.943**	.865**	.948**	-.063	1				
	Sig. (2-tailed)	.000	.000	.000	.771					
	N	24	24	24	24	24				
Nitrogen	Pearson Correlation	-.914**	.847**	.930**	-.120	.967**	1			
	Sig. (2-tailed)	.000	.000	.000	.575	.000				
	N	24	24	24	24	24	24			
Available Phosphorus	Pearson Correlation	-.805**	.783**	.909**	-.088	.923**	.923**	1		
	Sig. (2-tailed)	.000	.000	.000	.681	.000	.000			
	N	24	24	24	24	24	24	24		
potassium	Pearson Correlation	-.849**	.815**	.932**	-.047	.944**	.939**	.965**	1	
	Sig. (2-tailed)	.000	.000	.000	.826	.000	.000	.000		
	N	24	24	24	24	24	24	24	24	
Grain yield (t/ha)	Pearson Correlation	-.818**	.885**	.564**	.031	.700**	.697**	.610**	.660**	1
	Sig. (2-tailed)	.000	.000	.004	.884	.000	.000	.002	.000	
	N	24	24	24	24	24	24	24	24	24

***. Correlation is significant at the 0.01 level (2-tailed).*

Table 6. Correlation of Rice Yield and Soil Properties Under Rainfed Rice System

		Bulk Density	Porosity	WHC	Ph	Nitrogen	AP	OC	Potassium	GY(t/ha)
Bulk Density	Pearson Correlation	1								
	Sig. (2-tailed)									
	N	24								
Porosity	Pearson Correlation	.955**	1							
	Sig. (2-tailed)	.000								
	N	24	24							
Water Holding Capacity	Pearson Correlation	.873**	.795**	1						
	Sig. (2-tailed)	.000	.000							
	N	24	24	24						
pH	Pearson Correlation	-.236	-.107	-.376	1					
	Sig. (2-tailed)	.266	.619	.070						
	N	24	24	24	24					
Nitrogen	Pearson Correlation	.916**	.883**	.908**	-.278	1				
	Sig. (2-tailed)	.000	.000	.000	.189					
	N	24	24	24	24	24				
Available Phosphorus	Pearson Correlation	.831**	.793**	.911**	-.285	.901**	1			
	Sig. (2-tailed)	.000	.000	.000	.176	.000				
	N	24	24	24	24	24	24			
Organic carbon	Pearson Correlation	.958**	.906**	.948**	-.294	.956**	.915**	1		
	Sig. (2-tailed)	.000	.000	.000	.163	.000	.000			
	N	24	24	24	24	24	24	24		
potassium	Pearson Correlation	.869**	.833**	.932**	-.232	.934**	.966**	.938**	1	
	Sig. (2-tailed)	.000	.000	.000	.276	.000	.000	.000		
	N	24	24	24	24	24	24	24	24	
Grain yield (t/ha)	Pearson Correlation	.827**	.907**	.582**	.095	.747**	.620**	.729**	.676**	1
	Sig. (2-tailed)	.000	.000	.003	.660	.000	.001	.000	.000	
	N	24	24	24	24	24	24	24	24	24

***. Correlation is significant at the 0.0S1 level (2-tailed).*

Table 7. T-Test of Soil Properties and Seasons

Variable	Season	Mean	T- stat	P-value
Bulk Density	Irrigated	1.631	-5.251	0.000
	Rainfed	1.704		
Porosity	Irrigated	38.876	0.426	0.672
	Rainfed	38.651		
Water Holding Capacity	Irrigated	11.286	0.083	0.934
	Rainfed	11.234		
Hydraulic Conductivity	Irrigated	0.061	0.000	1.000
	Rainfed	0.061		
Ph	Irrigated	6.404	7.604	0.000
	Rainfed	6.104		
Organic Carbon	Irrigated	2.427	1.389	0.172
	Rainfed	2.376		
Nitrogen	Irrigated	0.275	2.533	0.015
	Rainfed	0.233		
Available Phosphorus	Irrigated	4.417	0.515	0.609
	Rainfed	4.371		
Potassium	Irrigated	0.278	6.746	0.000
	Rainfed	0.183		
Grain Yield	Irrigated	5.172	0.219	0.828
	Rainfed	5.047		

4. CONCLUSION AND RECOMMENDATION

The study demonstrated that integrated herbicide applications significantly influence soil physicochemical properties and rice grain yield in transplanted rainfed and irrigated systems in Makurdi. Moderate herbicide rates improved soil porosity and nutrient availability, enhancing grain yields above 6 t/ha, outperforming control and manual weeding. However, excessive herbicide use reduced soil organic carbon, nutrient levels, and increased compaction, adversely affecting soil health and yield. Irrigated soils showed better moisture regimes and nutrient status than rainfed soils, highlighting water management’s role in mediating herbicide effects.

It is recommended to adopt moderate integrated herbicide regimes tailored to local soil and water conditions, combining chemical and cultural weed control to optimise rice productivity while preserving soil fertility and structure for sustainable farming in Makurdi.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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