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Morpho-Agronomic Characterization of Twelve Upland Rice Cultivars in DR-Congo Oxisols

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Abstract

A field study was conducted during the 2025B growing season (February 17 to June 18, 2025) in the Ngandajika territory of the DRC to evaluate the morpho-agronomic potential of 12 rice genotypes under varying soil fertility management. The experiment, located at two sites—Mpoyi (Site 1) and the INERA Ngandajika station (Site 2) utilized a factorial design in Randomized Complete Blocks (RCBs) with two factors: fertilization (no fertilizer control vs. NPK 17-17-17 at 200 kg/ha) and 12 rice varieties. Each site featured two blocks (fertilized and unfertilized) with three replicates. Experimental units measured 2 m × 2 m (4 m^2) with 0.5 m spacing between plots and 1 m between blocks, for a total block area of 270 m^2 (30 m × 9 m). Fertilizer application significantly increased yields compared to the control: 1224 kg ha^{-1} (Site 1) and 1211 kg ha^{-1} (Site 2) with fertilizer, versus 1125 kg ha^{-1} (Site 1) and 1079 kg ha^{-1} (Site 2) without, while the site effect was minimal. Improved varieties showed superior performance across both conditions. Under fertilized conditions, NERICA4 (1843 kg ha^{-1}) performed best, followed statistically by IRAT112 (1837 kg ha^{-1}) and NERICA7 (1835 kg ha^{-1}), all of which outperformed INERA7 (1760 kg ha^{-1}), LIENGE (1753.3 kg ha^{-1}), and BOSAU (1737 kg ha^{-1}). Without fertilizer, IRAT112 (1692 kg ha^{-1}) was the top performer, followed by NERICA4 (1667 kg ha^{-1}), BOSAU (1653 kg ha^{-1}), INERA7 (1652 kg ha^{-1}), and NERICA7 (1627 kg ha^{-1}). While these yields are lower than intensive irrigated systems (5000 - 7000 kg ha^{-1}), they are comparable to West African regional averages for upland rice (1600 - 3000 kg ha^{-1}).

Keywords

Gandajika, Upland Rice Varieties, Mineral Fertilization, Yield, Oxisol

1. Introduction

Based on updated projections, the global population is anticipated to approach 9.8 billion by 2050 rather than 2030 presenting massive challenges for food security [1]. This surge, coupled with climate change, will likely double food requirements in Africa by 2050, putting severe pressure on the continent's agricultural systems [2]. A significant portion of the world's undernourished population is concentrated in a few nations, with the Democratic Republic of the Congo (DRC) consistently ranking among them due to ongoing conflict and food insecurity [3]-[5].

In the Democratic Republic of the Congo (DRC), where over 70% of the population resides in increasingly impoverished rural areas, the low productivity of traditional seed varieties remains a primary driver of food insecurity [6] [7]. Consequently, future agricultural recovery hinges on strategic investments. These must focus on improving access to high-quality inputs, enhancing soil fertility management, providing comprehensive training for stakeholders, and fostering participatory research that actively involves local farmers [8]-[10].

The government of the DRC plans to promote agriculture through a vision called the Aggressive Agricultural Revolution (AAR) which is part of the overall vision of the Head of State summarized in the revenge of the soil on the subsoil. This promotion aimed at increasing agricultural production must take into account soil management, eco-climatic conditions, crop diversification and the improvement of plant material.

Among the food crops generally grown in the Democratic Republic of the Congo and particularly in the Greater Kasai area, cereals occupy second place after roots and tubers. Among the cereals in the DR-Congo, rice (*Oryza sativa*) has emerged as a major staple crop, ranking in prominence immediately after maize [11] [12]. Rice has been cultivated in the Democratic Republic of the Congo (DRC) since around 1840, when it was introduced by Arab traders. For many years, its cultivation remained largely confined to the eastern regions of the country, particularly among Arabized communities around Kisangani and Maniema. Today, however, rice is increasingly recognized as a crop of strategic importance for the country's future and for national food security. Alongside cassava and plantain, it has become one of the principal staple foods in the DRC [11] [13].

In West Africa, rice productivity varies considerably depending on the cultivation system. Irrigated systems in countries such as Senegal and Mali can achieve yields of about 3 t ha^{-1}, whereas the regional average remains around 1.6 t ha^{-1}, largely due to the genetic limitations of upland rice varieties. Lowland rice varieties provide an opportunity to increase yields if key production factors—such as secure land tenure and access to mechanization—are improved. Nevertheless, the high cost of improved seeds represents a major market constraint, limiting the expansion of local rice production to rural areas while imported rice continues to dominate urban markets [14] [15].

In the Democratic Republic of the Congo (DRC), upland (rainfed) rice production is largely dominated by smallholder farming systems, which remain insufficient to meet the country's growing demand for rice [11] [12]. Historical data shows that in 1992, the DRC consumed 500,000 tonnes of rice, requiring 150,000 tonnes in imports. Local cultigens currently face genetic erosion due to various biotic and abiotic stressors [11] [12]. Since 1987, the National Institute for Agronomic Studies and Research (INERA) has operated the National Rice Research Programme (PNRR) at the Yangambi station to boost rice yield and quality. This program focuses on breeding interspecific hybrids by crossing local varieties (R66, OS6) with superior introductions (IRAT 2, IRAT 13) to incorporate essential agronomic traits. Geographically, over 72% of the DRC's rice production is concentrated in four key provinces: Orientale (28%), Maniema (20%), Equateur (13%), and Kasai Oriental (11%). While rainfed (upland) farming is the dominant system, aquatic rice cultivation is specifically implemented in hubs such as the Ruzizi plain, Kinshasa, and localized areas within Equateur, Kongo Central, and Katanga.

Beyond the established INERA varieties, the Democratic Republic of the Congo has inventoried several improved upland rice strains (Kasongo *et al.*, 2017) [16]. Specifically, a dozen varieties—including IRAT 112, INERA 5, 6, 7, 8, LIBOGA, LIENGE, LIOTO, BAIBINGE 1, NERICA 4, NERICA 7, and JASMINE—are currently maintained at INERA research stations. However, performance studies for these certified seeds have largely been confined to stations such as INERA Ngandajika in the Greater Kasai region, with only preliminary adaptation trials conducted elsewhere [16].

Rice production in Greater Kasai remains hampered by several critical constraints: the reliance on low-yield traditional or degenerated seeds, limited access to improved varieties, pest pressure from birds and locusts, and the continued use of rudimentary farming techniques [12]. Since farmer adoption largely depends on a variety's ability to outperform existing local seeds, the primary objective of this study was to evaluate the morpho-agronomic performance of twelve improved and local upland rainfed rice varieties across the diverse environments of Ngandajika, with the aim of identifying the most promising candidates for large-scale dissemination.

2. Materials and Methods

2.1. Study Environment

This study evaluated the performance of 12 rice varieties during the 2025 B growing season (February 17-June 18) across two locations in Ngandajika: Mpoyi (Site 1) and the INERA Ngandajika research station (Site 2). These sites were selected due to Mpoyi's extensive seed farming operations and INERA's role as a primary research hub. The map of Gandajika is described in **Figure 1**.

Mpoyi is geographically located at 6˚45′41.7″S and 24˚05′35.7″E, at an elevation of 652 m above sea level, whereas the INERA site is situated at 6˚48′29.3″S and 23˚57′25.7″E, with an elevation of 754 m above sea level. According to the Köppen climate classification, the region is characterized by an Aw3 tropical savanna climate, marked by an eight-month rainy season and a three-month dry season extending from mid-May to August. A brief dry spell in January/February divides the rains into two distinct growing seasons: A and B. The area maintains an average temperature of 25˚C and annual rainfall of approximately 1500 mm. Soil composition generally consists of sand-on-clay sediments over a shallow lateritic slab, featuring a well-saturated adsorption complex [17]-[20]. Muyayabantu *et al.* [19] reports very low levels of total and bioavailable nutrients at INERA site where soil was characterized by a sandy texture compared to Mpiana site where the soil texture is dominated by clay. Also, the agropedological monitoring of Mpoyi and Mpiana sites in Ngandajika territory revealed a major problem of physico-chemical degradation and acidification of soils due to the intensity of agricultural practices. Comprehensive physico-chemical characteristics of INERA site are detailed in Muyayabantu *et al.* [19].

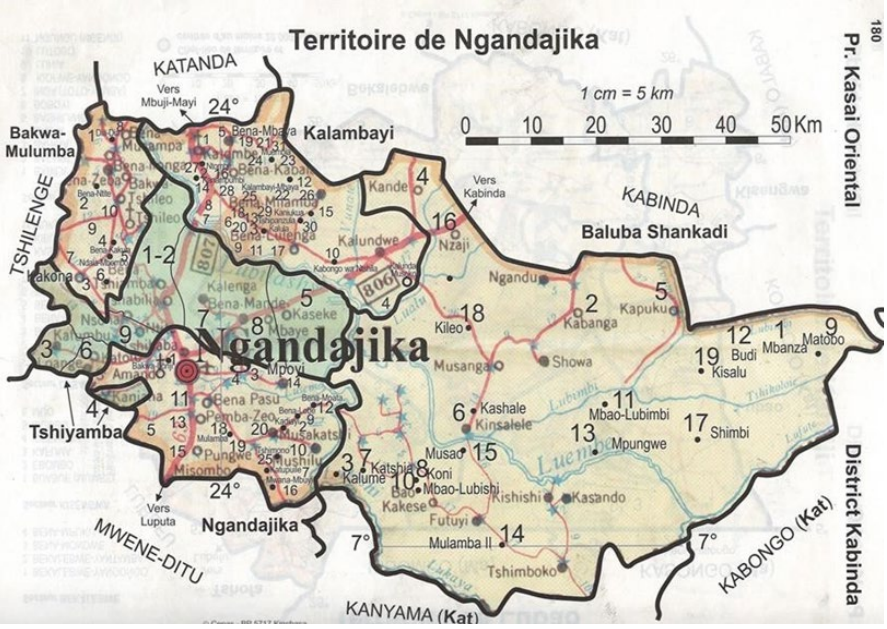


Figure 1. Map of Ngandajika.

2.2. Experimental Design and Plant Management

The study was conducted at two locations (the INERA station and Mpoyi) using a Randomized Complete Block Design (RCBD) with a two-factor structure. The primary factor comprised 12 rice varieties sourced from INERA Ngandajika, as presented in **Table 1**, while the secondary factor consisted of fertilization treatments (with fertilizer and without fertilizer). Each trial was replicated three times, covering a total area of 270 m^2 (30 m × 9 m). Experimental plots measured 2 m × 2 m (4 m^2), with 0.5 m spacing between plots and 1 m between blocks. Rice was sown in rows at a rate of 5 grains per hill, using a 25 cm × 25 cm spacing (equating to 156 hills per plot and a density of 781.25 grains per plot). For the fertilized treatments, NPK 17-17-17 was applied 20 days after sowing (JAS) at a rate of 200 kg/ha (equivalent to 34-34-34).

Table 1. Rice varieties used in our study in Ngandajika.

No.	Varieties	No.	Varieties
01	ART 672-F6	07	LIOTO
02	IRAT 112	08	INERA 7
03	ART 579	09	LIENGE
04	ART 626	10	BOSAU
05	NERICA 4	11	NERICA 7
06	ART 572/10	12	ART 572/14

2.3. Observations

The 12 rice varieties were evaluated as described in Mudibu *et al.*, Nkongolo *et al.*, and Mdoda *et al.* [10] [12] [21]. Data collection took place within a 2.25 m^2 observation square per plot, following diagonal sampling.

Evaluation Parameters

Plant and Grain Evaluation: Plant and grain characteristics were rated on a 1 - 5 scale, where 1 represents the best performance and 5 indicates poor performance. Plant appearance was assessed while plants were green, considering dry spikelets and fully developed panicles. Grain appearance, including color and size, was scored after sun drying. Disease and insect severity were rated on a scale from 1 (no or minimal symptoms) to 5 (severe manifestation).

Emergence density, measured as the number of seedlings, was recorded 14 days after planting. Flowering density, defined as total tillers, was assessed on 10 randomly selected and marked clumps at the flowering stage. Plant height was measured at maturity from the collar to the panicle tip. Production parameters were recorded at maturity from the same 10 randomly selected clumps and included 50% flowering date, panicle length, number of grains per panicle, 100-seed weight, plot production, and paddy yield. All collected data were subsequently analyzed using R software.

3. Results and Discussion

The various results obtained after analysis of the data collected are presented and commented on in the following sections.

3.1. Paddy Yield under Site-Treatment Interaction

The moisture content of sun-dried paddy ranged between 12% and 14%. Figure 2 shows the interaction between site and fertilization treatment on rice yield, highlighting how management practices and edapho-climatic conditions jointly influence the performance of improved upland rice. Overall, fertilizer application significantly increased yields ($P \leq 0.05$) compared to unfertilized plots at both sites: 1223.7 kg ha^{-1} vs. 1125 kg ha^{-1} at Site 1, and 1211.1 kg ha^{-1} vs. 1078.9 kg ha^{-1} at Site 2. In contrast, site location alone did not significantly affect production, as yields for the same treatment showed no statistical difference (P ≥ 0.05) between sites. This pattern was consistent for both unfertilized plots (Site 1: 1125 kg ha^{-1}; Site 2: 1078.9 kg ha^{-1}) and fertilized plots (Site 1: 1223.7 kg ha^{-1}; Site 2: 1211.1 kg ha^{-1}). These results align with the findings of Bedi *et al.* [6], who attribute low rice yields in the Democratic Republic of the Congo to inadequate soil fertility management and the use of low-performing varieties.

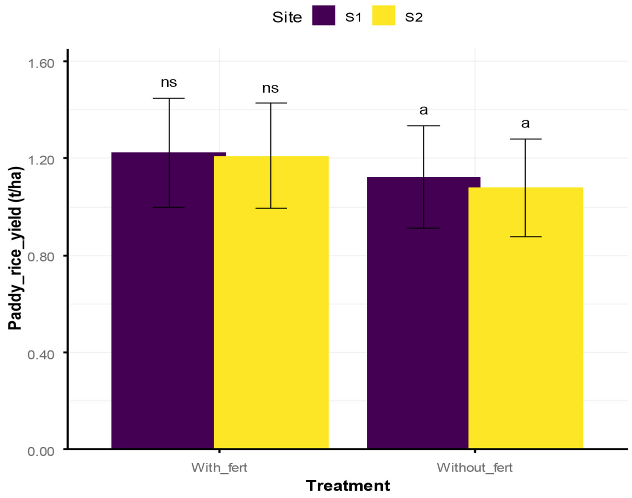


Figure 2. Effects of site interaction and fertilization practice on rice yield in the two sites in Ngandajika.

3.2. Site-Dependent Yield Performance of Paddy Rice Varieties

Site-specific performance of the evaluated rice varieties is illustrated in **Figure 3(a)** and **Figure 3(b)**. The data indicates that, despite variations in environmental conditions across locations, each variety maintained a consistent yield potential, suggesting that site-specific environmental factors such as rainfall, soil fertility, and agricultural practices had a limited impact on overall yield. Among the varieties tested, ART1, 2, 3, 4, and 5 demonstrated the lowest productivity, with yields ranging from 378.3 kg ha^{-1} (ART2 at site 1) to 436.7 kg ha^{-1} (ART5 at site 2). The top-performing varieties at site 1 were IRAT112 (1781.7 kg ha^{-1}), NERICA7 (1778.3 kg ha^{-1}), and NERICA4 (1771.7 kg ha^{-1}), which showed no statistically significant difference in yields (P ≥ 0.05).

While these findings show limited site influence, they contrast with reports of strong regional variations in upland rice productivity in West Africa [22] [23]. The observed intra-site variability in this study is likely driven by genotypic differences, soil heterogeneity, climatic factors, and biotic constraints such as bird and locust damage, which are commonly reported in smallholder farming systems in the DRC [12].

Based on the yields of the top-performing varieties (**Figure 3**), production is comparable to the West African regional average of approximately 1.6 t/ha but falls short of intensive irrigated systems elsewhere [24]. These findings align with conclusions from previous studies, which suggest that sustainable rice production improvement in the DR-Congo depends on adapting improved varieties locally, implementing reasonable fertilization, and effectively extending agricultural technologies [11] [12].

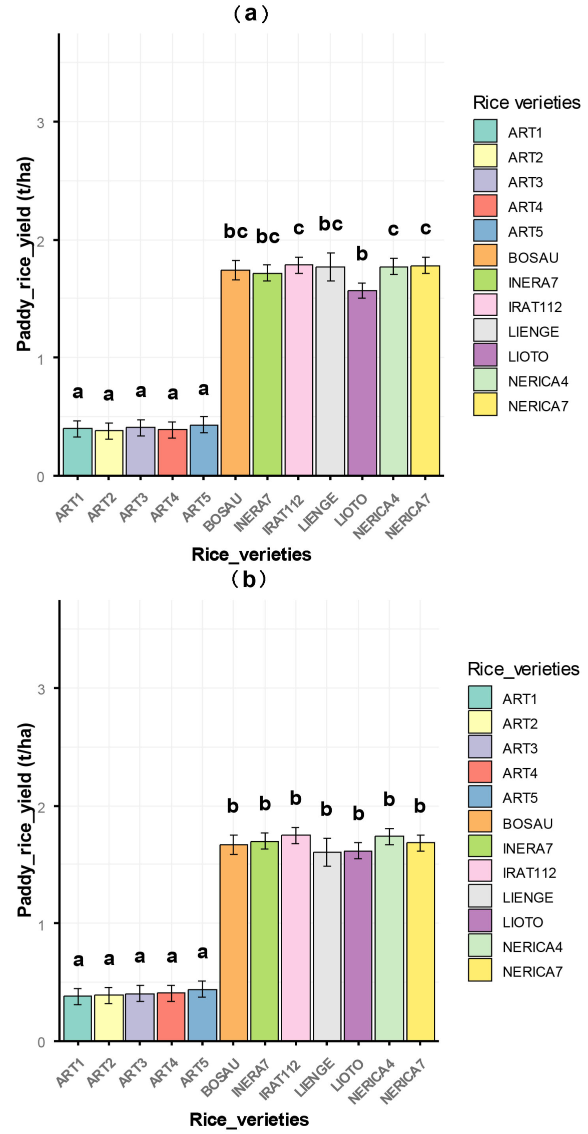


Figure 3. Yield of rice varieties by site; 3(a) represents data from site 1 and 3(b) site 2 (IC = 95%).

There is a clear separation between the less productive ART varieties and the rest of the more productive varieties (Figure 3(a)-(b)).

3.3. Effect of Treatments on Varietal Rice Yields

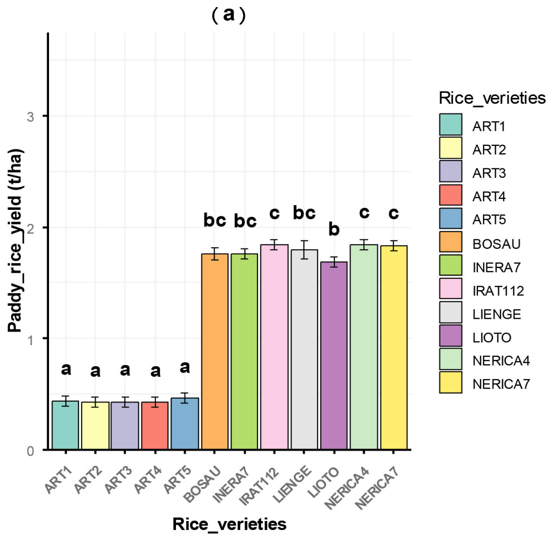
Rice production data (Figure 4(a) **and** Figure 4(b)) indicates that soil fertilization significantly affects paddy yield, with a marked gap observed between fertilized and unfertilized plots across most varieties. Under fertilized conditions, NERICA4 led with an average yield of 1843.3 kg ha^{-1}, performing statistically similarly ($P = 0.05$) to IRAT112 (1836.7 kg ha^{-1}) and NERICA7 (1835.0 kg ha^{-1}). A second group of high performers followed these: INERA7 (1760.0 kg ha^{-1}), LIENGE (1753.3 kg ha^{-1}), and BOSAU (1737.0 kg ha^{-1}).

IRAT112 was the top-performing variety (1691.7 kg ha^{-1}), with significantly higher yields ($P \leq 0.05$) than others, followed by a subset of four intermediate-performing varieties (NERICA4, BOSAU, INERA7, and NERICA7). Without fertilizer application, NERICA4 achieved a yield of 1666.7 kg ha^{-1}, followed by BOSAU (1653.3 kg ha^{-1}), INERA7 (1651.7 kg ha^{-1}), and NERICA7 (1626.7 kg ha^{-1})

The least productive varieties among all under study are ART 1, 2, 3, 4 and 5, whose yields in both cases are significantly less than 500 kg ha^{-1}. The performance observed of each variety during this study would be more related to intrinsic (genotype) than environmental (soil) properties. Even under nearly identical conditions, yield variability was evident across almost all rice varieties. This observation aligns with previous research highlighting significant yield increases in various genotypes when water and fertility management are optimized [21].

The high yields of BOSAU and NERICA varieties confirm their productive potential, supporting findings by Fukuta *et al.* [25] and Oikeh *et al.* [26] regarding their positive response to intensified conditions, while noting IRAT112's superior performance in non-fertilized environments. Conversely, the low, undifferentiated yields of ART varieties confirm the findings of Futakuchi *et al.* [23], demonstrating the limited performance of certain traditional varieties across both improved and unimproved conditions

Under SE conditions, the general yield decline and statistical homogeneity among varieties align with Audebert *et al.* [27], who noted a reduction in rice yield potential under environmental stress. However, NERICA and LIENGE maintained comparatively higher yields, suggesting superior tolerance. Consequently, this study confirms existing literature and underscores the value of adopting improved varieties particularly NERICA alongside optimized cultural practices to achieve sustainable yield increases.



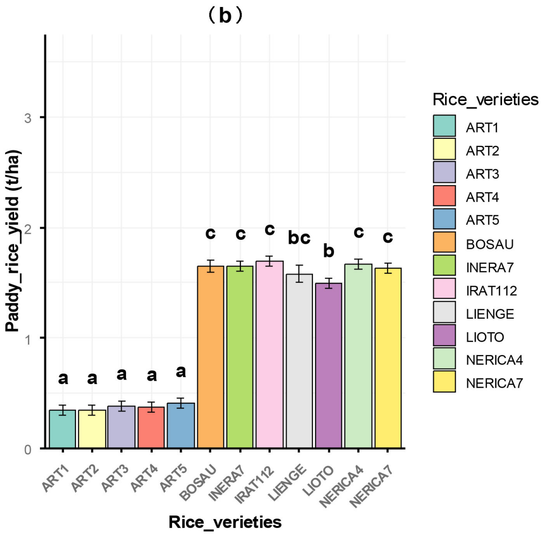


Figure 4. Rice yield as a function of fertilizer and variety interaction: 4(a) fertilized and 4(b) unfertilized soil areas (IC = 95%).

3.4. Rice Yield Variation Driven by the Interaction of Site, Management, and Genotype

Table 2 illustrates a significant three-way interaction between site, treatment, and variety regarding rice production. This indicates that paddy yield is co-dependent on the environment, fertilization strategy, and specific plant material. Such findings confirm that upland rice productivity is driven by the interplay between edapho-climatic conditions and genetic potential, aligning with previous reports by Nkongolo *et al.* [12].

In view of these results (**Table 1**), it appears that IRAT112 and NERICA7 are the most productive with 1.7817 kg ha^{-1} and 1.7783 kg ha^{-1} respectively at site 1. They are followed in descending order of NERICA4 with 1.7717 kg ha^{-1} still at site 1. A group of 3 varieties that hold each other in terms of yield, although relatively lower than the first 4 varieties, are also more productive. It is LIENGE in S1 with 1758.3 kg ha^{-1}; IRAT112 with 1746.7 kg ha^{-1} and NERICA4 with 1738.3 kg ha^{-1} at site 2 and BOSAU in S1 with 1728.7 kg ha^{-1}. These results show an expression of the marked interaction between site, fertilizer and variety. These results show that these high-performance varieties would effectively make the most of fertilizing elements when environmental conditions are favourable [28] [29].

Studies by Miyamoto *et al.* (2012) [30] corroborate the high yield potential of NERICA varieties. Conversely, the low yields observed across all varieties without fertilizer highlight the constraints of traditional farming systems. Furthermore, this genotype × environment interaction confirms that varietal adaptation is critical for upland rice productivity in the Democratic Republic of the Congo, supporting findings by Nkongolo *et al.* [12].

The ART 1 - 5 varieties produced consistently low yields across both locations, indicating restricted genetic potential and poor environmental adaptability. These findings align with Bedi (2017) [6], who identified the reliance on low-yielding traditional varieties as a primary driver of low rice productivity among Congolese farmers. In contrast, improved varieties such as NERICA 4, NERICA 7, IRAT 112, LIENGE, and LIOTO achieved significantly higher yields, though their performance fluctuated based on site conditions and fertilization. This variability supports the findings of other studies, which highlight that while NERICA varieties possess high production potential, they remain highly sensitive to local edapho-climatic factors [30].

At both sites, the varieties IRAT 112, LIENGE, and LIOTO demonstrated consistent yield stability across different environments. While their absolute yields differed from NERICA 7, their performance suggests superior phenotypic plasticity. As illustrated in **Figure 4(a)** and **Figure 4(b)**, this stability remained consistent regardless of fertilizer application. Such resilience is highly valued in the upland rice systems of Greater Kasai, where climatic variability is high and input control is minimal. Ultimately, the ability of these varieties to adapt to low-intensity conditions is a vital asset for local smallholder farms facing limited access to agricultural inputs.

Table 2. Evolution of rice yield as a function of combined site effects, treatment and varieties under different sites at Ngandajika.

Rice_varieties	Site 1		Site 2	
	With_fert	Without_fert	With_fert	Without_fert
ART1	0.417 ± 0.020^{cw}	0.377 ± 0.020^{cx}	0.447 ± 0.005^{cw}	0.313 ± 0.011^{cx}
ART2	0.410 ± 0.036^{cw}	0.347 ± 0.015^{cx}	0.433 ± 0.0351^{cw}	0.337 ± 0.020^{cx}
ART3	0.423 ± 0.025^{cw}	0.383 ± 0.058^{cx}	0.423 ± 0.0379^{cw}	0.380 ± 0.026^{cx}
ART4	0.403 ± 0.032^{cw}	0.373 ± 0.055^{cx}	0.440 ± 0.010^{cw}	0.367 ± 0.005^{cx}
ART5	0.443 ± 0.005^{cw}	0.410 ± 0.026^{cx}	0.473 ± 0.030^{cw}	0.400 ± 0.010^{cx}
BOSAU	1.770 ± 0.035^{bw}	1.690 ± 0.100^{abx}	1.710 ± 0.055^{abw}	1.620 ± 0.015^{ax}
INERA7	1.730 ± 0.075^{bw}	1.700 ± 0.010^{aw}	1.790 ± 0.032^{abw}	1.600 ± 0.005^{abx}
IRAT112	1.860 ± 0.045^{bw}	1.710 ± 0.015^{ax}	1.820 ± 0.037^{aw}	1.680 ± 0.020^{ax}
LIENGE	1.820 ± 0.045^{aw}	1.700 ± 0.020^{ax}	1.690 ± 0.139^{bw}	1.490 ± 0.055^{abx}
LIOTO	1.700 ± 0.140^{bw}	1.430 ± 0.041^{abx}	1.670 ± 0.050^{bw}	1.550 ± 0.005^{abx}
NERICA4	1.840 ± 0.037^{aw}	1.700 ± 0.017^{ax}	1.840 ± 0.040^{aw}	1.630 ± 0.011^{ax}
NERICA7	1.880 ± 0.040^{aw}	1.680 ± 0.046^{abx}	1.790 ± 0.032^{abw}	1.570 ± 0.020^{abx}
CV	4.47	4.65	4.1	2.6

The means followed by the same letter do not differ significantly at the 5% threshold according to Tukey HSD. The first set of letters a, b, c and d is used for comparison in columns (varieties); While the second series w and x, is used for the online comparison between without and with fertilization for the same site.

At site S2, fertilization also had a positive effect, though less pronounced than at site S1. This difference, likely stemming from variations in initial soil fertility, suggests that fertilizer alone cannot overcome environmental constraints. These findings support Bedi's (2017) conclusion [6] that low rice productivity in the

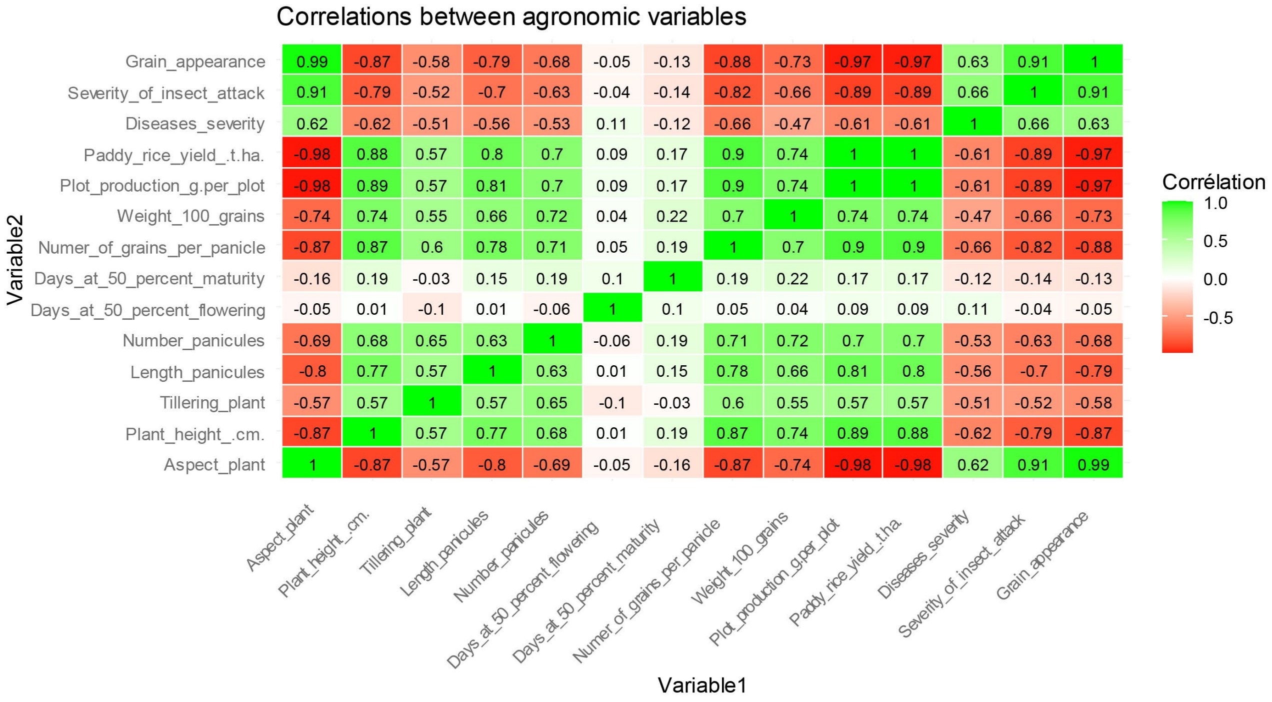
DRC results from multiple combined factors.

In contrast, varieties ART1 through ART5 produced low yields across all sites and treatments. Their weak response to fertilization suggests limited genetic potential, mirroring findings from Nkongolo *et al.* [12] regarding the poor performance of traditional local varieties.

Although the observed yields (**Figures 2-4** and **Figure 6**) are lower than the 5000 - 7000 kg ha^{-1} typically obtained in intensive irrigated systems, they are comparable to the average upland rice yields in West Africa (1600 - 3000 kg ha^{-1}) suggesting that the productivity levels observed in this study are consistent with regional production conditions [22] [29]. These findings underscore the urgency of boosting productivity in the DRC by introducing locally adapted varieties and implementing targeted extension strategies, as advocated by Mbuya *et al.* and Nkongolo *et al.* [3] [4].

3.5. Correlation Analysis of Key Morpho—Agronomic Parameters and Paddy Rice Yield

Figure 5 indicates that paddy yield is strongly associated with several key agronomic traits, notably 1000-kernel weight, number of panicles per plant, number of kernels per panicle, and plot production weight. These strong positive correlations suggest that enhancing these yield components can directly increase productivity, regardless of differences in variety, environment, or fertilization practices. This observation is consistent with previous studies by Nkongolo *et al.*, Mudibu *et al.*, and Nkongolo *et al.* [8] [10] [12].



	Aspect_plant	Plant_height_.cm.	Tillering_plant	Length_panicules	Number_panicules	Days_at_50_percent_flowering	Days_at_50_percent_maturity	Numer_of_grains_per_panicle	Weight_100_grains	Plot_production_g.per_plot	Paddy_rice_yield_.t.ha.	Diseases_severity	Severity_of_insect_attack	Grain_appearance
Grain_appearance	0.99	-0.87	-0.58	-0.79	-0.68	-0.05	-0.13	-0.88	-0.73	-0.97	-0.97	0.63	0.91	1
Severity_of_insect_attack	0.91	-0.79	-0.52	-0.7	-0.63	-0.04	-0.14	-0.82	-0.66	-0.89	-0.89	0.66	1	0.91
Diseases_severity	0.62	-0.62	-0.51	-0.56	-0.53	0.11	-0.12	-0.66	-0.47	-0.61	-0.61	1	0.66	0.63
Paddy_rice_yield_.t.ha.	-0.98	0.88	0.57	0.8	0.7	0.09	0.17	0.9	0.74	1	1	-0.61	-0.89	-0.97
Plot_production_g.per_plot	-0.98	0.89	0.57	0.81	0.7	0.09	0.17	0.9	0.74	1	1	-0.61	-0.89	-0.97
Weight_100_grains	-0.74	0.74	0.55	0.66	0.72	0.04	0.22	0.7	1	0.74	0.74	-0.47	-0.66	-0.73
Numer_of_grains_per_panicle	-0.87	0.87	0.6	0.78	0.71	0.05	0.19	1	0.7	0.9	0.9	-0.66	-0.82	-0.88
Days_at_50_percent_maturity	-0.16	0.19	-0.03	0.15	0.19	0.1	1	0.19	0.22	0.17	0.17	-0.12	-0.14	-0.13
Days_at_50_percent_flowering	-0.05	0.01	-0.1	0.01	-0.06	1	0.1	0.05	0.04	0.09	0.09	0.11	-0.04	-0.05
Number_panicules	-0.69	0.68	0.65	0.63	1	-0.06	0.19	0.71	0.72	0.7	0.7	-0.53	-0.63	-0.68
Length_panicules	-0.8	0.77	0.57	1	0.63	0.01	0.15	0.78	0.66	0.81	0.8	-0.56	-0.7	-0.79
Tillering_plant	-0.57	0.57	1	0.57	0.65	-0.1	-0.03	0.6	0.55	0.57	0.57	-0.51	-0.52	-0.58
Plant_height_.cm.	-0.87	1	0.57	0.77	0.68	0.01	0.19	0.87	0.74	0.89	0.88	-0.62	-0.79	-0.87
Aspect_plant	1	-0.87	-0.57	-0.8	-0.69	-0.05	-0.16	-0.87	-0.74	-0.98	-0.98	0.62	0.91	0.99

Figure 5. Correlation analysis data illustrating the relationships between morpho-agronomic parameters and paddy yield at Ngandajika (mean of two sites).

In addition, **Figure 5** shows that paddy yield is moderately improved by greater tillering, increased plant height, and longer panicles. This pattern indicates that vigorous and well-developed plants are more likely to achieve higher yields, supporting the relationship between vegetative growth and productivity highlighted by Nkongolo *et al*. [12]. Conversely, yield is negatively affected by higher levels of disease severity and insect attack. This finding agrees with Bedi *et al*. [6], who emphasized that biotic stresses remain a major constraint to upland rice production in the Democratic Republic of the Congo.

The heatmap further illustrates the relationships among agronomic variables, revealing several notable patterns. Grain appearance is strongly and positively correlated with both insect attack severity and disease severity, suggesting that grain visual characteristics may be influenced by biotic stress conditions. However, grain appearance is strongly negatively correlated with yield-related traits such as paddy yield and plot production, indicating that visually appealing grains do not necessarily reflect higher productivity. As expected, paddy yield and plot production are almost perfectly positively correlated. Both variables also show strong positive associations with the number of grains per panicle, panicle length, and plant height, underscoring the importance of plant structure and reproductive traits in determining yield. Likewise, the number of grains per panicle and panicle length are key contributors to yield performance.

Plant height and tillering exhibit moderate to strong positive correlations with yield, suggesting that more vigorous plants tend to be more productive. However, these traits are negatively correlated with grain appearance and stress-related variables, pointing to a possible trade-off between plant growth and susceptibility or grain quality. Finally, days to 50% flowering and maturity display generally weak correlations with most variables, indicating that phenological traits may have a limited influence on yield and grain quality compared to structural and reproductive characteristics in this study.

Figure 6 presents the Principal Component Analysis (PCA) projections for variety and treatment. The data variability is primarily driven by Axis 1 (65.3%), while Axis 2 contributes only 8.5%, revealing a dominant gradient in the observation structure. The partial separation between fertilization treatments identifies nutrient application as a key driver of the multivariate structure. This aligns with findings from Bationo *et al*. [31], which suggest that fertilization triggers an integrated system response in tropical agroecosystems. Nevertheless, the overlap and dispersion within treatments point to significant intra-treatment variability, likely due to the inherent spatial heterogeneity of tropical soils [29] [32].

The wider dispersion observed within the fertilized group reflects heterogeneous responses to nutrient application. Such variability is typical of low-fertility cropping systems, where the efficiency of added inputs is strongly influenced by soil conditions and the use of integrated fertility management strategies [28]. Accordingly, this PCA demonstrates that fertilization serves as a key structuring factor, while also underscoring the importance of integrated, site-specific approaches to reduce response variability and support sustained long-term productivity.

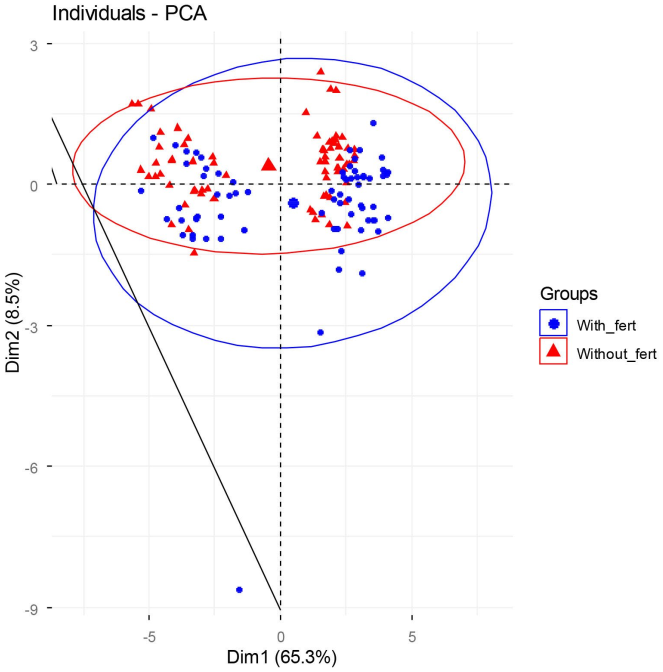


Figure 6. Visualizing variety and treatment interactions Principal component analysis.

4. Conclusion

This study underscores the critical roles that site location, fertilization, and genetic material play in determining the yield of upland rice in the Democratic Republic of the Congo. While fertilizer application significantly enhanced paddy yields, the effectiveness of these treatments was highly dependent on local edapho-climatic conditions and specific variety traits. Significant interactions between site × treatment, variety × treatment, and site × variety further demonstrate that upland rice productivity is context-specific. Improved varieties—notably NERICA 7, NERICA 4, IRAT 112, LIENGE, and LIOTO—consistently outperformed traditional ART varieties. For instance, NERICA 7 showed high environmental sensitivity, performing well at site S1 but declining at site S2. In contrast, IRAT 112, LIENGE, and LIOTO exhibited greater phenotypic plasticity, maintaining stable yields across different environments. Conversely, the poor performance of ART varieties across all conditions confirms their limited genetic potential and supports their replacement with locally adapted, improved varieties. The primary limitation of this study is that the recommendations are derived from a single growing season, two study locations, and one fertilizer rate. Consequently, the findings should be interpreted with caution and require further validation through multi-location, large-scale trials to confirm their broader applicability.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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