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Agronomic Performance of Rice–Wheat Intercropping in an Upland Area of the Bouaké Region, Central Côte d'Ivoire

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Authors' contributions

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

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Abstract

In the context of climate change, innovative rice-based cropping systems represent a sustainable approach to improving agricultural productivity. Given the reduction in cultivable land and declining soil fertility, assessing the effects of intercropping under different fertilisation regimes is essential in order to improve yield potential and eco-efficiency in rice–wheat cropping systems in Côte d'Ivoire. Accordingly, the agronomic performance of rice–wheat intercropping and of each crop grown as a monoculture was evaluated using a split-plot experimental design with three replications. Four treatments were tested: an absolute control without input (T2), a Costus–Kaolin–Polifol biofertiliser combination (T1), a combination of conventional fertilisers (NPK and 46% N urea) with Costus–Kaolin biofertilisers (T3), and conventional fertilisers alone, consisting of NPK and 46% N urea (T4). The number of tillers, percentages of insect and bird damage to rice, straw biomass, daily productivity, and grain yield per hectare were measured. The area time equivalent ratio (ATER), grain and straw yields, and harvest index (HI) were also determined.
The results showed that the intercropping system significantly increased rice grain yield, with 2.4 t/ha under intercropping compared with 1.5 t/ha under monoculture. Conversely, wheat achieved its highest grain yield under monoculture, with 1.5 t/ha

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compared with 0.7 t/ha under intercropping. Treatment T3 was the most effective across the cropping systems. System daily productivity (P = 31 kg/ha/day) and an ATER greater than 1 confirmed the agronomic advantage of rice–wheat intercropping.

Keywords: Rice; wheat; intercropping system; fertilization; yield; soil amendment; weeds; biodiversity.

1. Introduction

Bread wheat (*Triticum aestivum*) and rice (*Oryza sativa* L.) are major staple crops in Africa and play a key role in food security and nutrition across the continent (Mendez del Villar & Bauer, 2013). These two crops support the livelihoods of millions of smallholder farmers and contribute to dietary diversity. However, the current upland rice production model is becoming less competitive in the face of increasing population demand. The scarcity of arable land and the effects of climate change further highlight the need to explore alternative crop diversification models, particularly intercropping systems.

Recent field evidence from rice-based intercropping further indicates that crop pairing and configuration can influence yield performance under aerobic conditions (Gami et al., 2024). In wheat-based systems, intercropping outcomes likewise vary with species combination, spatial arrangement, and nitrogen management (Ma et al., 2024; Raza et al., 2024; Xia et al., 2024).

Wheat has become an important component of diets in West Africa. However, local production remains limited, and consumption is still highly dependent on imports (Al-Taufik & Garbrah, 2022). African countries are therefore among the world's leading wheat importers, with more than 45 million tons imported in 2013 at an estimated cost of USD 15 billion, placing pressure on national economies (Macauley & Ramadjita, 2015). In 2020, local rice production covered only 80% and 60% of demand in sub-Saharan Africa and Africa as a whole, respectively (OECD & FAO, 2015). This low performance is generally attributed to inadequate management of agricultural land and cropping systems.

In West Africa, Côte d'Ivoire has climatic diversity and a relatively flat landscape that are favourable to rice production. Nevertheless, upland rice production faces several structural and climatic constraints that limit productivity. To mitigate risks associated with monoculture and cope with climatic variability, the adoption of rice–wheat intercropping, which consists of growing both species simultaneously on the same plot, appears to be a promising alternative. This practice could improve land-use efficiency, increase cultivated biodiversity, reduce certain biotic pressures, and promote more efficient use of soil resources.

Evidence from rice-based intercropping also suggests that organic nutrient amendments can influence yield and crop nutritional responses under mixed cultivation (Rani & Kapoor, 2023).

However, despite the recognised benefits of intercropping systems, limited information is available on the agronomic performance of rice–wheat intercropping under the upland conditions of central Côte d'Ivoire. Furthermore, little evidence exists regarding the interaction between this cropping system and different fertilisation strategies, including the combined use of conventional fertilisers and biofertilisers. Therefore, the objective of this study was to evaluate the agronomic performance of rice–wheat intercropping compared with the respective monocultures under different fertilisation regimes. We hypothesised that (i) rice–wheat intercropping would improve land-use efficiency and overall system productivity compared with monocultures, and (ii) the combination of conventional fertilisers and biofertilisers would enhance crop performance more effectively than either practice used alone.

2. Materials

2.1 Study Site

The study was conducted at the M'bé Agricultural Research Station, located 37 km from Bouaké in the Gbèkè region. The site is characterised by a gently undulating landscape composed of low plateaus, plains, and inland valleys, at an altitude of 270 m above mean sea level (geographical coordinates: N 07°87′113″; W 005°11′722″). The climate is humid tropical, with alternating dry and rainy seasons. The rainy season generally extends from April to October, while the dry season occurs from December to March. Temperatures range from 25 °C to 35 °C, and annual rainfall varies from 1,000 to 1,700 mm, with high spatial and temporal variability. The average duration of the dry season is approximately 105 days per year, and average relative humidity is estimated at 74% (Avenard, 1971; Dabin et al., 1960; Dje et al., n.d.).

2.1.1 Plant Material

Two cultivated species were used in this study:

- **NERICA 4** (New Rice for Africa 4), used as the main crop. This upland rice variety has a 90-day growth cycle, a potential yield of 4 t/ha, and an average plant height of approximately 1.5 m. Developed by AfricaRice, formerly WARDA, it is recognised for its drought tolerance (Centre du riz pour l'Afrique [ADRAO], 2008).

- **DIRE 10** (*Triticum aestivum*, bread wheat, commercial variety from ICARDA), used as the associated crop. This variety has a 120-day growth cycle, a potential yield of 3 to 4.5 t/ha, and a plant height ranging from 1 to 1.5 m (Macauley & Ramadjita, 2015).

The selection of these varieties was based on yield potential and adaptation to the edaphic, environmental, and climatic conditions of the study site (Traoré et al., 2016).

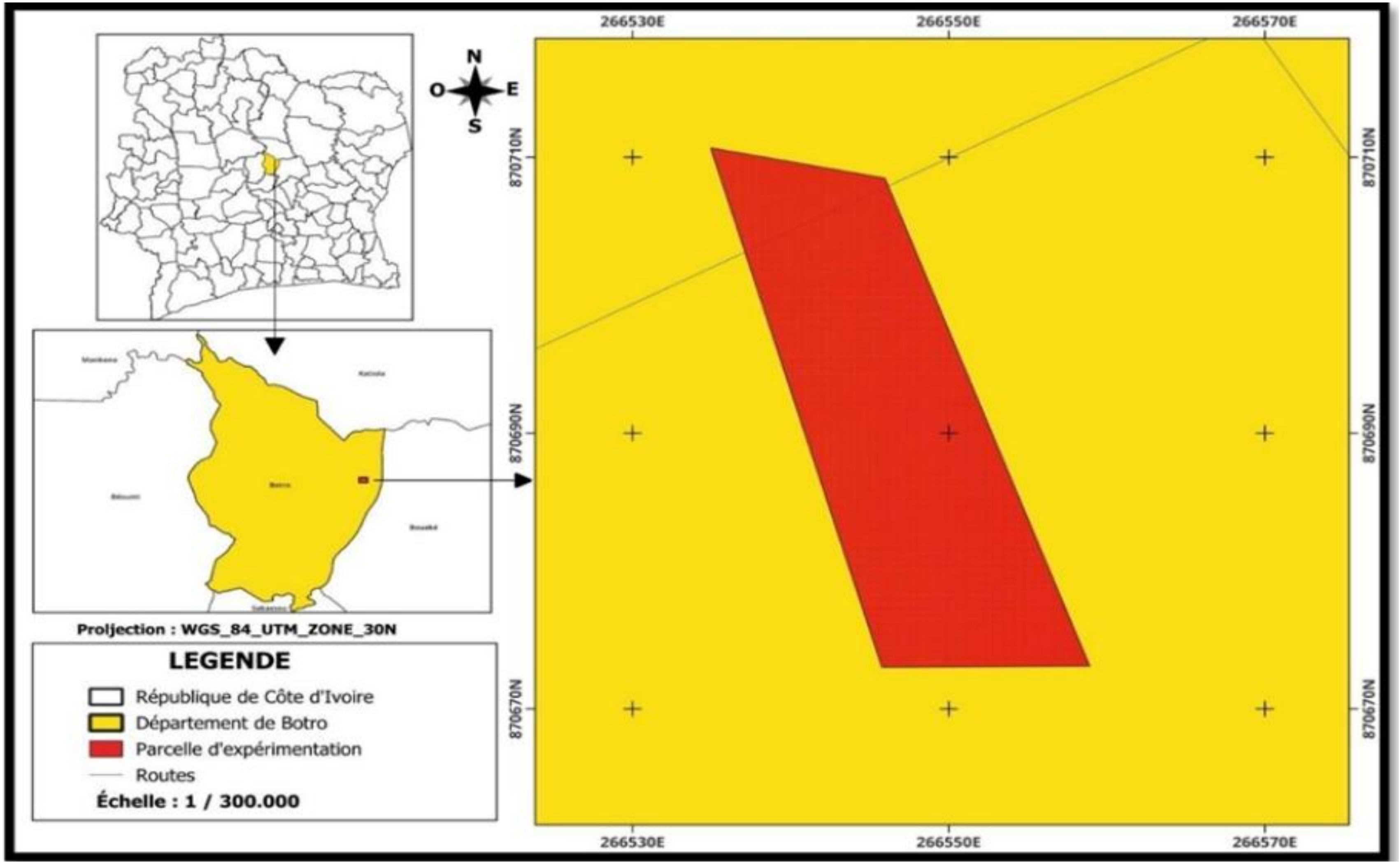

Fig. 1. Location of the M'bé agronomic experimental site

2.1.2 Treatments

Throughout the trial, the crops were subjected to the following treatments in each replication.

The four fertility treatments were applied under each cropping system in every replication, resulting in twelve treatment combinations (3 cropping systems × 4 fertility treatments) per replication.

2.2 Methods

2.2.1 Soil Profile Description

The soil profile was described from a pedological pit by recording general information, environmental conditions, and profile characteristics. The description was based on the observation of the following criteria: horizon thickness and boundaries, measured using a measuring tape; transitions between horizons, including colour and consistency; colour according to the Munsell chart; estimated organic matter content; moisture status; texture determined by the tactile method; coarse fragments, including concretions, gravel, and quartz, visually observed; general structure; aggregate cohesion; and horizon type (O, A, B, and C). Soil classification was performed according to the WRB reference system (IUSS Working Group WRB, 2015).

2.2.2 Establishment of the Experiment

Establishment of the experiment included soil preparation through double ploughing, plot layout using the 3-4-5 method based on the Pythagorean theorem to ensure right angles, application of basal fertilisers, direct manual sowing of rice and wheat, and manual irrigation. The experimental design was a split-plot arrangement with three replications.

Fig. 2. The 3-4-5 method used for plot layout

Fig. 3. Application of HK granules (*Costus afer* and kaolin) as basal fertilizer

Fig. 4. Manual sowing of wheat and rice

2.3 Experimental Design

Two factors were evaluated in this study: the cropping system and fertility management. The cropping system factor comprised three levels: rice monoculture, wheat monoculture, and rice–wheat intercropping. Fertility management consisted of four treatments (T1, T2, T3, and T4) described in Table 1. The experiment was established as a split-plot design with three replications in order to account for field heterogeneity and the operational constraints associated with the intercropping system. The cropping systems were assigned to the main plots, whereas the fertility management treatments were allocated to the subplots within each replication.

Table 1. Treatment characteristics and application methods

Treatment	NPK (15-15-15)	HK — *Costus afer* + kaolin	Urea (46%)	Polifol
T1 — Biofertilizers	—	500 g × 3	—	10 ml/L × 3
T2 — Control without input	—	—	—	—
T3 — Conventional + biofertilizers	300 g (21 DAS)	500 g × 3	112.5 g × 2	—
T4 — Conventional fertilizers alone	300 g (21 DAS)	—	112.5 g × 2	—

DAS: days after sowing. HK: Costus afer–kaolin granules. —: not applied. HK and Polifol were applied as basal fertilizer, at tillering, and at heading; NPK was applied 21 DAS; urea was applied only at tillering and heading.

Within each replication, the fertility treatments were randomly assigned to the subplots before sowing to minimise positional effects and ensure the independence of experimental units. Each elementary plot measured 3 m × 2.5 m (7.5 m²). The spacing between blocks was 1 m, while adjacent subplots were separated by 0.5 m.

Fig. 5. Experimental layout at the site after plot marking and sowing

2.4 Data Collection

Data were obtained from direct field measurements and from agronomic calculations performed after harvest.

2.4.1 Measured Variables

Measurements were taken from the central area of each plot in order to reduce border effects. For each plot, observations were performed on a 1 m² sampling unit. Five types of variables were measured: number of tillers, number of panicles or spikes, percentage of insect damage, percentage of bird damage, and straw biomass. Straw biomass was determined by weighing samples from two 1 m² quadrats per elementary plot after drying.

2.4.2 Calculated variables

Because crop durations differed between species, the efficiency of the intercropping system was assessed using the area time equivalent ratio (ATER), calculated according to Hiebsch and McCollum (1987):

$$\text{ATER} = \Sigma \ \frac{\text{Rendement relatif} * \text{Durée de culture}}{\text{Durée total d'occupation}} \qquad \text{[Eq. 1]}$$

where the relative yield (R) of each crop was calculated as follows:

$$\text{R} = \frac{\text{Rendement en association}}{\text{Rendement en monoculture}} \qquad \text{[Eq. 2]}$$

System daily productivity (P) was calculated as follows:

$$\text{P (kg/ha/j)} = \frac{\text{Rendement équivalent total}}{\text{Durée totale d'occupation (jours)}} \qquad \text{[Eq. 3]}$$

Grain yield (kg/ha) = (grain mass per quadrat / quadrat area) × 10,000 [Eq. 4]
Straw yield (kg/ha) = (straw mass per quadrat / quadrat area) × 10,000 [Eq. 5]

Straw yield was determined in the field using a spring balance.

Total dry matter (TDM) = grain yield + straw yield. [Eq. 6]

The harvest index (HI) corresponded to the ratio of grain yield to total dry matter, multiplied by 100.

HI = (grain yield / total dry matter) × 100 [Eq. 7]

2.4.3 Data Processing and Statistical Analysis

Agronomic data were first subjected to descriptive statistical analysis using Microsoft Excel and subsequently analysed by analysis of variance (ANOVA) using R software version 4.5.1. The ANOVA model included cropping system, fertility management, and their interaction as fixed effects, while replication was considered as a blocking factor. When significant effects were detected, treatment means were separated using the Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$).

3. Results

This section presents and analyses the results obtained from the field experiment.

3.1 Edaphic Conditions of the Experimental Site

Table 2. Description of the soil pit.

Depth	Horizon description
0–10 cm	O1 horizon: 10YR 7/2, humiferous, sandy loam, porous, granular structure, presence of subhorizontal roots (cm to mm), distinct transition, discontinuous boundary, good biological activity, no constraint.
10–24 cm	O2 horizon: 10YR 6/3, humiferous, sandy clay, less porous, granular structure, presence of numerous subhorizontal roots (cm to mm), abrupt transition, regular boundary, good biological activity, no constraint.
24–70 cm	A horizon: 10YR 5/4 reddish yellow, non-humiferous, sandy, no biological activity, slightly porous, 50% rounded coarse fragments (quartz and gravel) ranging from mm to cm, single-grain structure, diffuse boundary, presence of ferruginous concretions.
70–130 cm	B horizon: 5YR 5/6, non-humiferous, mottled (ochre, red, orange), clayey texture, non-porous, polyhedral structure, low content of coarse fragments, compact. Horizon rejuvenated by renewed weathering of the hardpan. Constraint: high clay content.

WRB classification (IUSS Working Group WRB, 2015): Plinthic Ferralsol. The humiferous layer exploitable by roots was approximately 25 cm thick

A soil pit was opened on the lower slope, within a geological context dominated by a granito-gneissic basement and fallow vegetation. The soil profile description is presented Table 2.

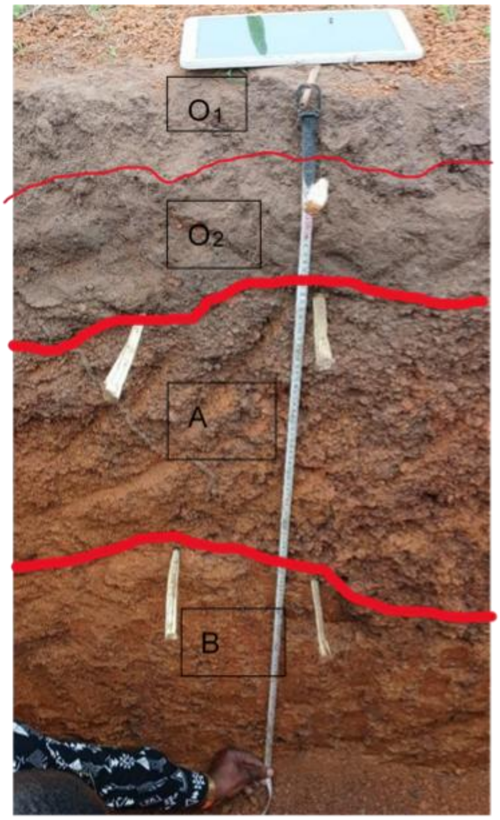

Fig. 6. Plinthic Ferralsol soil profile at the M'bé station, Bouaké

3.2 Vegetative Performance and Fertility Management Practices

The duration of plot occupation differed among cropping systems: rice monoculture had a three-month cycle, whereas rice under rice–wheat intercropping occupied the plot for three months and 20 days. The wheat cycle was similar under both intercropping and monoculture conditions, lasting three months. Analysis of variance for the number of tillers and panicles/spikes revealed significant variation among cropping systems ($p < 0.05$), whereas fertility management (F) and the cropping system × fertility management interaction (S × F) showed no significant effect (Table 3).

Table 3. Probability values (p-values) associated with tiller number and panicle/spike number according to the studied factors

Factor	Rice tillers	Wheat tillers	Rice panicles	Wheat spikes
Cropping system (S)	< 0.001	< 0.001	0.0065	< 0.001
Fertility management (F)	ns	ns	ns	ns
S × F interaction	ns	ns	ns	ns

ns: not significant at p = 0.05

Table 4. Number of tillers and panicles/spikes according to cropping system (mean ± standard deviation)

Cropping system	Rice tillers	Wheat tillers	Rice panicles	Wheat spikes
Rice monoculture	9.9 ± 0.3 b	—	8.5 ± 0.4 b	—
Wheat monoculture	—	21.1 ± 2.2 a	—	18.4 ± 2.1 a
Rice–wheat intercropping	12.1 ± 0.4 a	11.3 ± 0.7 b	10.3 ± 0.5 a	9.2 ± 0.7 b
LSD	1.12	4.81	—	4.65

Means followed by different letters within the same column are significantly different at p = 0.05 according to the LSD test. —: not applicable

Under intercropping, rice produced an average of 10 to 12 tillers per hill, whereas wheat showed greater variability, with 11 to 21 tillers per hill. Rice formed an average of 9 to 10 panicles per hill, while wheat produced 9 to 18 spikes per hill.

According to fertility management practices, rice maintained a relatively stable tillering level, ranging from 10 to 12 tillers per hill. Wheat, however, showed a more variable response, with an average of 13 to 20 tillers per hill. The number of rice panicles ranged from 8 to 11, whereas the number of wheat spikes ranged from 11 to 18 per hill.

3.2.1 Grain Yield and Fertility Management

Analysis of variance revealed highly significant differences among cropping systems ($p < 0.001$) for rice and wheat grain yield, wheat biomass yield, and rice harvest index. In contrast, rice biomass yield and wheat harvest index did not differ significantly according to cropping system. For fertility management, significant differences were observed for wheat grain yield ($p = 0.0343$), rice biomass ($p < 0.001$), wheat biomass ($p = 0.0095$), and wheat harvest index ($p < 0.001$), whereas rice grain yield and rice harvest index did not vary significantly according to this factor (Table 5).

Table 5. Probability values (p-values) for grain yield, biomass yield, and harvest index according to the studied factors

Factor	Rice GY (t/ha)	Wheat GY (t/ha)	Rice biomass	Wheat biomass	Wheat HI	Rice HI
Cropping system (C)	< 0.001	< 0.001	ns	< 0.001	ns	< 0.001
Fertility management (F)	ns	0.0343	< 0.001	0.0095	< 0.001	ns
C × F interaction	ns	ns	ns	0.0017	0.0017	0.0141

GY: grain yield; HI: harvest index; ns: not significant at p = 0.05.

Grain yield ranged from 1.5 to 2.4 t/ha for rice and from 0.7 to 1.5 t/ha for wheat, depending on the cropping system. Wheat grain yield according to fertility management was highest under T3 (1.5 t/ha) and T4 (1.4 t/ha), lower under T1 (1.0 t/ha), and lowest under T2 (0.5 t/ha). Total biomass yield was highest under T3 and T4, with 5.0 and 4.7 t/ha, respectively, compared with lower values under T2 and T1, with 3.6 and 3.1 t/ha, respectively (Table 6).

Table 6. Paddy yield, biomass yield, and harvest index by cropping system and treatment (mean ± standard deviation)

Factor / treatment	Rice GY (t/ha)	Wheat GY (t/ha)	Rice biomass (t/ha)	Wheat biomass (t/ha)	Total biomass (t/ha)
Cropping system					
Rice monoculture	1.5 ± 0.1 b	—	3.1 ± 0.2 b	—	3.1 ± 0.2 b
Rice–wheat intercropping	2.4 ± 0.1 a	0.7 ± 0.1 b	3.6 ± 0.2 a	1.3 ± 0.1 b	4.9 ± 0.3 a
Wheat monoculture	—	1.5 ± 0.2 a	—	4.3 ± 0.5 a	4.3 ± 0.5 a
LSD	0.346	0.395	0.624	1.010	—
Fertility management practice					
T1 — Biofertilizers	1.9 ± 0.2 a	1.0 ± 0.2 ab	2.4 ± 0.1 b	2.2 ± 0.5 a	3.1 ± 0.2 b
T2 — Control	1.6 ± 0.4 a	0.5 ± 0.1 b	3.3 ± 0.3 a	2.1 ± 0.4 a	3.6 ± 0.4 b
T3 — Conventional + biofertilizers	2.1 ± 0.2 a	1.5 ± 0.4 a	3.9 ± 0.1 a	3.7 ± 1.2 a	5.0 ± 0.5 a
T4 — Conventional fertilizers alone	2.0 ± 0.2 a	1.4 ± 0.3 a	3.9 ± 0.2 a	3.2 ± 0.9 a	4.7 ± 0.3 a
LSD	—	0.73	—	—	0.63

GY: grain yield. Means followed by different letters within the same column section are significantly different at p = 0.05 according to the LSD test. —: not applicable.

Fig. 7 presents grain yield, expressed in tonnes per hectare, for the three cropping systems: rice monoculture, rice–wheat intercropping, and wheat monoculture, under the four fertilisation treatments (T1, T2, T3, and T4). The results show that rice yield was higher under intercropping than under monoculture. Conversely, wheat reached its maximum yield under monoculture, reflecting a different response of the two species to the intercropping system. Among the fertilisation treatments, T3 showed the best overall performance, followed by T4, whereas the control treatment T2 remained the least effective for wheat grain yield.

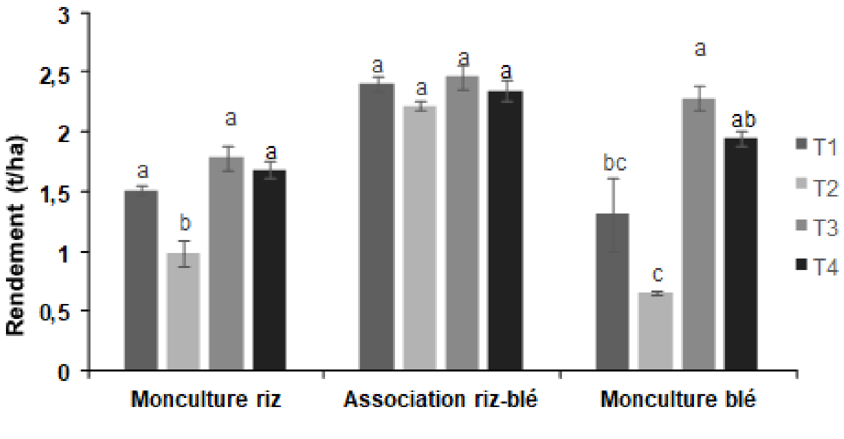

Fig. 7. Paddy yield of rice and wheat according to cropping system and fertilization treatment (t/ha)

Fig. 8 presents biomass yields, expressed in tonnes per hectare, according to cropping system and fertility management practice. The highest biomass yield was observed in wheat monoculture, followed by rice–wheat intercropping and then rice monoculture. Regarding fertilisation, treatments T3 and T4 produced the highest biomass yields.

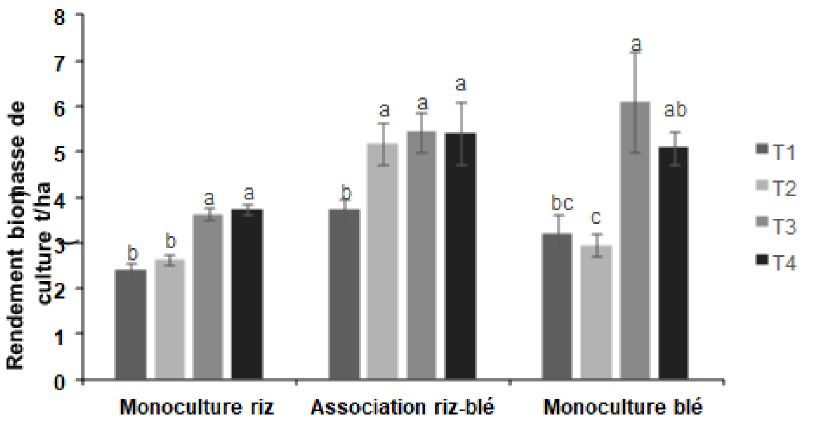

Fig. 8. Biomass yield of rice and wheat according to cropping system and fertilization treatment (t/ha)

The effect of cropping system was particularly marked for grain yield in both species, whereas fertility management mainly influenced wheat yield and biomass production. These results indicate that rice–wheat intercropping modified the distribution of performance between the two crops, with a clear advantage for rice and a greater constraint for wheat.

However, the absence of significant differences for some variables, particularly under the effect of fertilisation, indicates that observed trends should be interpreted with caution when treatment differences are not statistically confirmed.

3.2.2 System Productivity

System daily productivity (P) varied among treatments: approximately 18 kg/ha/day for T1, 27 kg/ha/day for T2, 31 kg/ha/day for T3, and 20 kg/ha/day for T4. The maximum value was recorded under T3. However, differences among treatments were not statistically significant ($p > 0.05$).

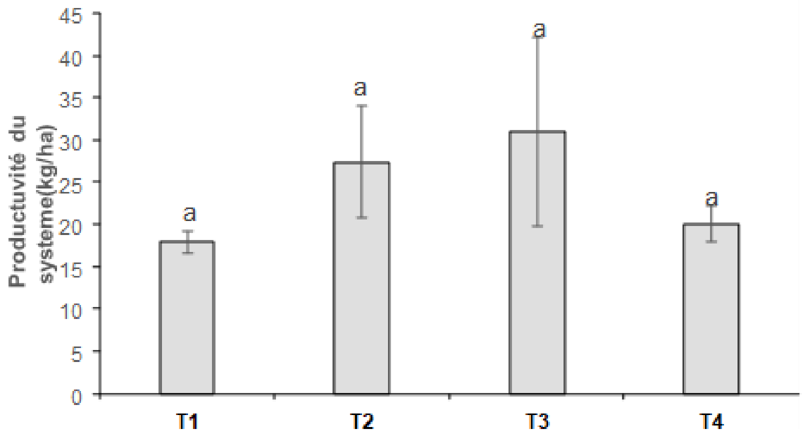

Fig. 9. System daily productivity (kg/ha/day) according to fertilization treatment

3.2.3 Area Time Equivalent Ratio (ATER)

Fig. 10 presents the area time equivalent ratio (ATER) for the four fertilisation treatments (T1, T2, T3, and T4).

ATER values were greater than 1 for all four treatments, indicating an overall advantage of rice–wheat intercropping compared with monocultures. The highest values were observed under T2 and T3. The corresponding increases were approximately 18.9% for T2 and 28.6% for T3 compared with T4. However, no significant difference was detected among treatments.

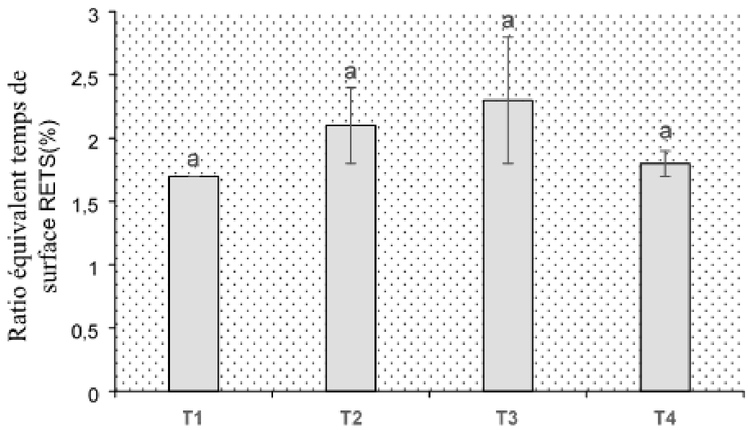

Fig. 10. Area time equivalent ratio (ATER) according to fertilization treatment (T1 to T4)

3.3 Biotic Constraints

The number of rice plants attacked by birds was significantly lower under intercropping (2.0 ± 0.3) than under rice monoculture (2.8 ± 0.3). However, the percentage of attacks was higher under intercropping (19.6%) than under monoculture (11.2%) because different denominators were used to calculate the percentages. Thus, intercropping appeared to reduce the absolute number of attacked plants, but the percentage of attack should be interpreted with caution (Table 7).

Table 7. Incidence of bird damage on rice according to cropping system (number of attacked plants per m² and percentage)

Cropping system	Attacked plants (per m²)	Attack percentage (%)
Rice monoculture	2.8 ± 0.3 a	11.2 ± 1.1 b
Rice–wheat intercropping	2.0 ± 0.3 b	19.6 ± 2.6 a
LSD	0.79	5.93

Means followed by different letters within the same column are significantly different at p = 0.05 according to the LSD test. Note: percentage denominators differed between systems (10 hills under intercropping and 25 hills under monoculture).

The insect damage parameters on wheat did not all differ significantly according to cropping system. However, significant differences were observed for the number of attacked hills (p = 0.0258), the number of damaged tillers (p = 0.0409), and the number of damaged panicles/spikes (p = 0.0347) (Table 8).

Table 8. Probability values (p-values) associated with insect damage on wheat according to the studied factors

Factor	Attacked hills	Attack incidence	Damaged tillers	Damaged panicles/spikes	Tiller severity	Panicle/spike severity
Cropping system (S)	0.0258	ns	0.0409	0.0347	ns	ns
Fertility management (F)	ns	ns	ns	ns	ns	ns
S × F interaction	ns	ns	ns	ns	ns	ns

ns: not significant at p = 0.05

The magnitude of insect damage varied between cropping systems, although not all observed differences were statistically significant. Wheat panicles/spikes appeared to be more affected under rice–wheat intercropping (6.6) than under monoculture (5.3), suggesting increased wheat susceptibility when grown in association.

Table 9. Incidence and severity of insect damage on wheat according to cropping system (mean ± standard deviation)

Cropping system	Attacked hills	Attack incidence	Damaged tillers	Damaged panicles/spikes	Tiller severity	Panicle/spike severity
Wheat monoculture	1.9 ± 0.3 a	7.3 ± 1.5 a	0.9 ± 0.1 a	0.9 ± 0.1 a	4.3 ± 0.6 a	5.3 ± 0.8 a
Rice–wheat intercropping	1.1 ± 0.2 b	6.4 ± 1.5 a	0.5 ± 0.1 b	0.6 ± 0.1 b	4.3 ± 1.0 a	6.6 ± 1.2 a
LSD	0.69	—	0.38	0.31	—	—

Means followed by different letters within the same column are significantly different at p = 0.05 according to the LSD test. —: non-significant difference.

Table 9 compares the effects of insect damage on wheat under monoculture and rice–wheat intercropping. The number of attacked hills was significantly lower under intercropping (1.1) than under wheat monoculture (1.9). In contrast, no significant difference was observed for overall attack incidence, with values of 7.3 under monoculture and 6.4 under intercropping. The numbers of damaged tillers and damaged panicles/spikes were also significantly lower under intercropping, with values of 0.5 and 0.6, respectively, compared with 0.9 for each variable under monoculture. Damage severity on tillers and panicles/spikes did not differ significantly between the two systems.

4. Discussion

4.1 Crop Yield Performance

Yield components, particularly the number of tillers and panicles, differed markedly according to crop species and production system. Rice grown in association produced more tillers and panicles than rice grown as a monoculture, whereas the opposite trend was observed for wheat. This divergence suggests that rice benefited from more favourable growth conditions under intercropping, while wheat may have experienced stronger competition or a mismatch between its physiological requirements and the fertilisation schedule, which was primarily aligned with the rice growth cycle. The relative yield values (R = 0.47 for wheat and R = 1.6 for rice) confirmed the clear advantage of the association for rice. This result was further supported by an ATER greater than 1, indicating the superior productive efficiency of the rice–wheat intercropping system. ATER values greater than 1 have also been reported in other intercropping systems, including sorghum–bottle gourd (Chimonyo *et al*., 2016), cowpea–cotton (Kalonda, 1993), and maize–legume systems (Inuganti et al., 2025).

Rice-equivalent yield, calculated by converting wheat yield into rice units based on market prices (Anjeneyulu et al., 1982), reached 4.7 t/ha under rice–wheat intercropping, compared with 1.5 t/ha for rice monoculture. These results are consistent with those reported by Ahmad et al. (2007) for rice–maize intercropping. Through intercropping, the agronomic potential of non-legume species such as wheat grown in association with upland rice could be enhanced (Saeed *et al*., 1999). Intercropping may also improve soil fertility and nutrient-use efficiency (Patra *et al*., 1986), while enabling more efficient use of land, labour, and capital resources (Morris & Garrity, 1993).

The better performance of rice under intercropping may be explained by the microclimatic conditions created by the presence of wheat, which may have supported upland rice growth, although this configuration slightly prolonged the vegetative cycle. This extension of the crop cycle may also be related to sowing during the dry season, which was characterised by high temperatures and low humidity (Salgotra & Chauhan, 2023; Tricker et al., 2018). Intercropping could therefore have partially mitigated these constraints. The high yield of wheat under monoculture indicates that the climatic conditions of the study area were relatively favourable for wheat cultivation (Traoré et al., 2016).

Fertility management was a key determinant of system performance. Data on tillering and panicle formation showed that some vegetative traits were occasionally higher under T4 than under T3. However, grain yield was higher under T3, suggesting that the combination of conventional fertilisers and biofertilisers may have provided a better balance between vegetative growth and grain formation.

4.2 Assessment of Pest Incidence

4.2.1 Insect Damage

The severity of insect damage did not show an overall significant difference between cropping systems. However, wheat spikes were more affected under intercropping (6.6) than under monoculture (5.3), contrary to the hypothesis that intercropping systematically reduces pest pressure (Baudry *et al*., 2024; Risch, 1981). This observation is consistent with studies showing that crop association may, in some cases, increase pest pressure on one of the cultivated species (Djian-Caporalino et al., 2024). Conversely, rice panicles were less affected under intercropping than under monoculture, suggesting a localised protective effect of intercropping on rice, consistent with the habitat diversity hypothesis (Root, 1973).

4.2.2 Bird Damage

The objective of rice–wheat intercropping was to disrupt bird foraging behaviour. The adopted strategy consisted of sowing wheat before rice so that wheat plants present during rice maturation could act as a physical barrier. In this study, the number of attacked rice plants was lower under intercropping, whereas the percentage of attack was higher because of the calculation method used. These results should therefore be interpreted with caution and do not support a generalised conclusion regarding protection against birds.

5. Study Limitations

This study provides valuable information on the agronomic performance of rice–wheat intercropping under the upland conditions of central Côte d'Ivoire. However, some limitations should be acknowledged. First, the fertilisation schedule was primarily designed according to the phenological requirements of rice and may not have fully matched the nutrient requirements of wheat throughout its longer growth cycle. Second, the experiment was conducted at a single site and during one growing season, which may limit the extrapolation of the results to other environments and years. Third, bird damage percentages were calculated using different sampling denominators in monocropping and intercropping systems; therefore, percentage comparisons should be interpreted with caution, whereas absolute counts provide a more reliable basis for comparison. Finally, additional studies including different wheat varieties, fertilisation schedules adapted to both crops, and multi-season evaluations would be useful to confirm the robustness of the observed trends and the agronomic potential of rice–wheat intercropping in Côte d'Ivoire.

6. Conclusion

Wheat cultivation in Côte d'Ivoire has already been investigated in previous studies that identified agroecological zones potentially suitable for its development (Traoré et al., 2016). Building on these earlier findings, the present study evaluated the agronomic performance of rice–wheat intercropping under the soil and climatic conditions of central Côte d'Ivoire. The main findings are summarised as follows:

- Rice significantly benefited from the intercropping system, with a grain yield of 2.4 t/ha compared with 1.5 t/ha under monoculture. Conversely, wheat achieved its highest yield under monoculture. Nevertheless, the overall efficiency of the intercropping system was confirmed by an ATER greater than 1 across all treatments and by a maximum daily productivity of 31 kg/ha/day, indicating a productive advantage of the association compared with separate monocultures.

- Treatments T3, combining conventional fertilisers and biofertilisers, and T4, based on conventional fertilisers alone, showed the best agronomic performance across the cropping systems. Treatment T3 appeared particularly promising for the intercropping system because of its agronomic stability and favourable benefit–cost ratio. In contrast, the unfertilised control treatment resulted in the lowest agronomic performance, particularly in rice monoculture.

- Rice–wheat intercropping exerted a partial protective effect on some biotic parameters, particularly by reducing the absolute number of rice plants attacked by birds and some insect damage observed on wheat. However, attack percentages and the severity of certain damage symptoms indicate that this effect was not systematic. These complex ecological interactions warrant further investigation through complementary studies.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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