American Journal of BioScience
2025, Vol. 13, No. 6, pp. 197-209
https://doi.org/10.11648/j.ajbio.20251306.12

SciencePG
Science Publishing Group

Research Article

Improvement of Growth and Biomass of Rice (*Oryza* sp., Nerica L14 Variety) by Mineral Fertilization over Two Successive Ratoon Cycles

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Abstract

Rice, one of the world's main cereal crops, is not only a source of grain, but also of straw. However, global rice production remains insufficient, particularly in West Africa, where extensive farming is hampered by demographic and economic pressures. Intensification systems, including the cultivation of rice ratoon from improved varieties, appear to offer a promising solution. This study, conducted in Ivory Coast, aimed to assess the effects of the mineral fertilization on the growth and biomass production of NERICA L14 rice ratoons across two successive cycles. Fertilizer rates of 100 $kg.ha^{-1}$ nitrogen 55 $kg.ha^{-1}$ phosphorus, 150 $kg.ha^{-1}$ potassium, 33 kg ha^{-1} calcium, 15 $kg.ha^{-1}$ magnesium, and 10 $kg.ha^{-1}$ zinc were applied, along with an unfertilized control plot (0 $kg.ha^{-1}$). The experiment was conducted in a randomised complete block design with four replications. Before ratooning, all elementary plots had received a basal application of 200 $kg.ha^{-1}$ NPK (10-18-18) and 35 $kg.ha^{-1}$ urea (46% N) at tillering and heading stages of the main crop. Observations and measurements were conducted on plant height, tiller density, and straw yield. Successive ratoon cycle exerted a depressive effect on both growth (reductions of up to 31.37% for plant height, and 42.41% for tillering), and straw yield (reduction of up to 65.87%) from one cycle to the next. Applications of nitrogen (73.15 and 65.05 cm for first and second cycles; 611 $tillers.m^{-2}$ and 2,898.44 $kg.ha^{-1}$ in total), zinc (70.6 and 61.88 cm; 565 $tillers.m^{-2}$ and 2,296.88 $kg.ha^{-1}$) and potassium (71.6 and 59.08 cm; 584 $tillers.m^{-2}$ and 2,187.50 $kg.ha^{-1}$) significantly increased these parameters, whereas calcium (66.28 and 50.9 cm; 465 $tillers.m^{-2}$ and 1,914.06 $kg.ha^{-1}$) exhibited a neutral to depressive effect across all ratoon cycles. Consequently, nitrogen, zinc, and potassium can be recommended as part of a rational fertilization strategy in ratoon culture, aiming to enhance vegetative growth and straw production of rice in Ivory Coast.

Keywords

Rice Ratooning, Mineral Fertilization, Rice Growth, Straw Yield, Ivory Coast

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Received: 7 October 2025; **Accepted:** 21 October 2025; **Published:** 26 November 2025

1. Introduction

Rice (*Oryza* sp.) is an annual herbaceous grass primarily cultivated in tropical regions for its grains [1]. It provides 20% of the global dietary energy supply, compared with 19% from wheat and 5% from maize [2]. Globally, it ranks as the third most consumed cereal after wheat and maize [3]. In 2023, global rice production was estimated at approximately 800 million tons, cultivated over 168.36 million hectares with an average grain yield of 4.75 tons per hectare. This positioned rice as the third leading crop in terms of global production, after sugarcane and maize [4]. Although primarily destined for human consumption, rice cultivation also generates substantial residues, particularly straw, of which only 20% is effectively utilized in industry and livestock feeding. The remainder is either burned or incorporated into soils [5]. Global rice straw production is estimated to exceed 700 million tons [6]. Several studies on the characterization and valorization of rice straw have highlighted the necessity of ensuring its production in both sufficient quantity and adequate quality, a major challenge for agricultural research [5, 7]. To address this, improved rice varieties have been developed. These varieties are hardy, with short growth cycles ranging from 90 to 100 days, and are better adapted to African rice-growing regions [8, 9]. Moreover, their straw yields are remarkably high [10]. However, yield improvement through the expansion of cultivated land is no longer sustainable due to intense land pressure, driven by population growth [11].

Despite the cultivation of improved varieties and the adoption of intensification techniques, combining fertilizers with best agricultural practices, rice production (both paddy and straw) has stagnated and remains insufficient [12-14]. An alternative pathway for intensification lies in the exploitation of successive ratoon cycles on the same plot immediately following the harvest of the main crop. In such systems, the yields (paddy and straw) from the main crop are complemented by those of the ratoons. Recent studies under tropical conditions report that ratoon yields average 50% of those of the main crop [15, 16]. In West Africa, the agronomic feasibility and economic potential of ratoon-based rice systems have been demonstrated [17]. Under irrigated conditions with fertilization, ratoons can secure straw yields exceeding 14 $t\ ha^{-1}$ [10] and grain yields ranging from 6 to 8 $t.ha^{-1}$ [18, 19]. Given the crucial role of mineral nutrients in rice cultivation [20], it appeared necessary to investigate their impact on the growth and straw yield of rice ratoons over two successive cycles.

The present study aims to enhance the growth performance and biomass production of the NERICA L14 rice variety through mineral fertilization under two consecutive ratoon cycles. The objectives of this research are to:

1) evaluate the effect of successive ratoon cycles on the height, number of tillers, and straw yield of NERICA L14 rice;
2) evaluate the effect of mineral fertilization on the height, and number of tillers of NERICA L14 rice over two successive ratoon cycles;
3) evaluate the effect of mineral fertilization on the straw yields of NERICA L14 rice under the same conditions.

2. Materials and Methods

2.1. Study Site

The present study was conducted on a 1,053 m^2 plot in a lowland area in the Dabou City, at 05°21′48″ N latitude, 04°22′51″ W longitude, and an altitude of 80 m. Dabou is in southern Ivory Coast, approximately 49 kilometers west of Abidjan, the country's economic capital [21].

2.2. Plant Material

The plant material used in this study was the rice variety NERICA L14, whose seeds were provided by the AfricaRice research station in Bouake, Ivory Coast. This interspecific variety was selected for its good agronomic performance. It has a short growth cycle of 110-115 days, a potential grain yield of 5 $t.ha^{-1}$, a straw yield of 14 $t.ha^{-1}$, and a strong capacity for ratooning. The ratoon crops reach maturity within 45 days per cycle under irrigation and fertilization conditions [10, 18, 19].

2.3. Methods

2.3.1. Field Preparation and Establishment of Rice Plots

At the study site, a 1,050 m^2 plot (39 m × 27 m) was demarcated using a measuring tape. Chemical weeding of the plot was carried out by spraying 0.5 L of glyphosate (360 $g.L^{-1}$) diluted in 51 L of water, using a 16 L capacity knapsack sprayer. Two weeks later, the plot was manually cleared with a machete, and the plant residues were removed from the site and burned [22]. The plot was then subdivided into four blocks, each consisting of seven rectangular elementary plots measuring (3 m × 5 m). Within each block, elementary plots were separated by a 0.5 m wide and high small dikes. A 0.5 m wide drainage canal was established between successive blocks, resulting in three canals separating the four blocks. These canals were connected perpendicularly to two collector canals, each 1 m wide on either side of the plot [22]. Water from the two collectors drained into a main canal oriented along the slope of the field. Finally, each elementary plot was irrigated for 24 hours, after which mud filling was carried out over two weeks through deep manual tillage with a hoe [23]. During mud filling, the water layer was maintained between 80 and 110 mm.

2.3.2. Rice Transplanting and the Main Crop

A basal application of 200 kg.ha^{-1} of NPK fertilizer (10-18-18 formulation) was incorporated into each elementary plot. Subsequently, 21-day old NERICA L14 seedlings from a nursery were transplanted at one per hole, spaced 20 cm x 20 cm apart [24]. At tillering and heading stages manual weeding was carried out and 35 kg.ha^{-1} of urea (46% N) was applied manually to each elementary plot [25]. At 80% maturity, the rice plants were harvested with a sickle (Figures 1a, 1b) at 15 cm above ground level [17, 22].

2.3.3. First and Second Ratoon Cycles

One day after the main crop harvest, manual weeding was conducted. Subsequently, basal applications of mineral fertilizers were carried out in each block, according to a randomised complete block design with four replicates (Figure 1c). Fertilizers were manually applied at the recommended rates described by Kouakou et al. [22] and Kone et al. [23, 26]: 100 kg.ha^{-1} of nitrogen (N) as urea (46%); 55 kg.ha^{-1} of phosphorus (P_2O_5) as triple superphosphate (TSP); 150 kg.ha^{-1} of potassium (K) as potassium chloride (KCl); 33 kg.ha^{-1} of calcium (Ca) as calcium carbonate ($CaCO_3$); 15 kg.ha^{-1} of magnesium (Mg) as magnesium sulfate ($MgSO_4$); and 10 kg.ha^{-1} of zinc (Zn) as zinc sulfate ($ZnSO_4$). Forty-five days later, at maturity (80%), the rice was harvested as in the main crop. Then, the second ratoon cycle was cultivated in the same way as the first ratoon cycle. During each ratoon cultivation cycle, a single manual weeding was carried out before flowering.

2.3.4. Experimental Design

The experimental design for the two consecutive ratoon cycles was a randomised complete block with four (4) replications of seven (7) treatments. The factor studied for each ratoon cycle was the fertilizer, comprising various mineral elements (Ca, K, Mg, N, P, Zn) and an untreated control (Te). Each elementary plot corresponded to a fertilizer treatment and contained 416 rice plants spaced at 20 cm × 20 cm. The experimental design was maintained identically for the second ratoon cycle as in the first (Figure 1c).

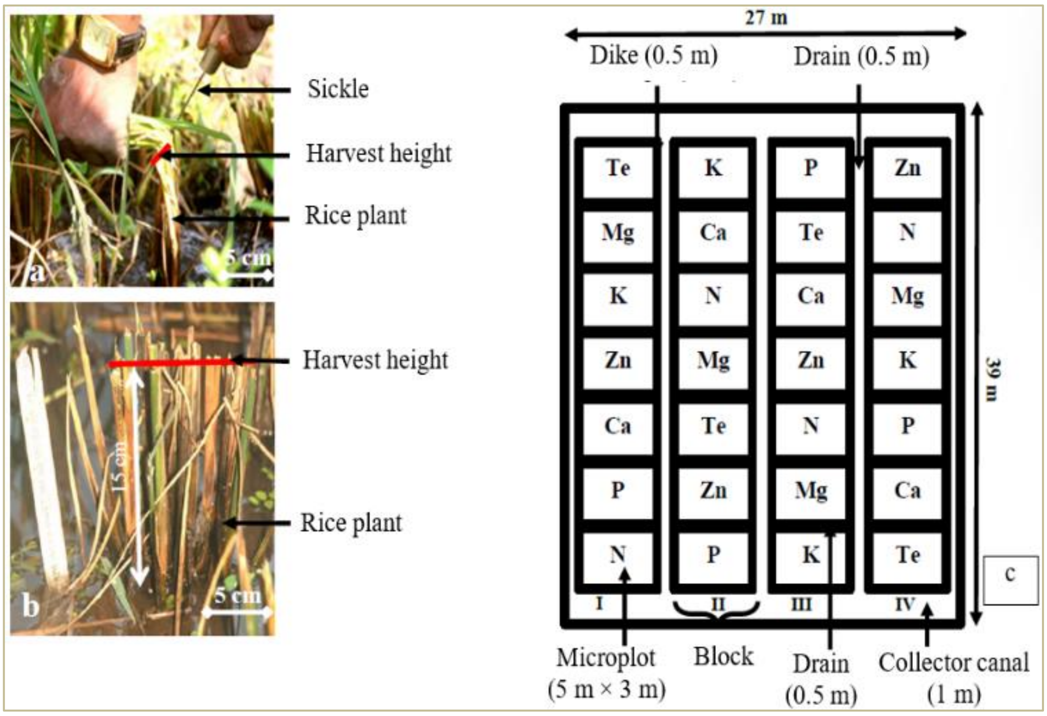

Figure 1. *Harvesting (a), NERICA L14 plant after harvest (b) and experimental design (c).*

2.3.5. Data Collection

Plant height was measured at full maturity, from the collar at ground level to the tip of the longest leaf on the rice plant [27] on 36 plants (6 ×6) within an observation square (1 m ×1 m) randomly selected in each elementary plot [28]. Measurements were conducted using a 150 cm measuring tape mounted on a wooden support.

The number of tillers per rice plant within the observation square was determined by manual counting at full maturity. The sum of these counts represented the number of tillers per square meter [27].

At full maturity, rice plants were harvested at 15 cm above ground level over an area of 8 m^2 in each elementary plot, excluding the two border rows [29]. Following threshing, the straw was collected, sun-dried for 15 days, and weighed using a dial scale. The obtained mass was used to calculate straw yield (SY) expressed in $kg.ha^{-1}$, adapted from the formula described by Kouakou et al. [22]:

$$SY\left(\frac{kg}{ha}\right) = \frac{Mass\ of\ harvested\ straw\ (g)}{Harvested\ area\ (m2)} \times \frac{10{,}000}{1{,}000} \quad (1)$$

For each fertilizer treatment in a ratoon cycle, the increment rates of plant height, number of tillers, and straw yield were calculated on the unfertilized control. The calculation was performed using the following formula:

$$Increment\ rate\ of\ x\ (\%) = \frac{\bar{x}\ fertilized - \bar{x}\ control}{\bar{x}\ control} \times 100 \quad (2)$$

Where, x̄ fertilized = mean of the parameter x (plant height, number of tillers or straw yield) in the fertilized treatment; x̄ control = mean of the parameter x (plant height, number of tillers or straw yield) in the control treatment.

Also, on a global scale and by treatment, the increment rates of plant height, number of tillers, and rice straw yield were calculated for ratoon cycles on the previous cycles using the following equation:

$$Increment\ rate\ of\ x(\%) = \frac{\bar{x}Cn - \bar{x}C(n-1)}{\bar{x}C(n-1)} \times 100 \quad (3)$$

Where, x̄Cn = mean of the parameter x (plant height, number of tillers, or straw yield) in cycle n; x̄C (n−1) = mean of the parameter x (plant height, number of tillers, or straw yield) in the previous cycle (n−1)

2.3.6. Statistical Analysis of Data

Data were analysed using XLSTAT version 2016. For each variable, the normality and the homogeneity of variances were assessed using the Shapiro-Wilk and Bartlett tests respectively. Depending on the assumptions met, either one-way analysis of variance (ANOVA) or the non-parametric Kruskal-Wallis test was applied to evaluate the effects of consecutive ratoon cycles and fertilizer treatments on rice growth parameters and straw yield. When significant differences were detected, means were separated into homogeneous groups using Duncan's or Dunn's test at a 5% significance level ($\alpha = 0.05$).

3. Results

3.1. Effect of Successive Ratoon Cycles on Rice Plant Height, Number of Tillers, and Straw Yield

The succession of ratoon cycles revealed a progressive and significant decrease ($p < 0.0001$) in plant height, number of tillers and straw yield of NERICA L14 rice (Table 1). The highest averages of these parameters 85.18 cm, 382 $tillers.m^{-2}$ and 2,584.82 $kg.ha^{-1}$ were recorded in the main crop, where all plots were fertilized with NPK and urea. It is followed by the first ratoon cycle (68.98 cm, 326 $tillers.m^{-2}$, 1,233.54 $kg.ha^{-1}$). The lowest values of plant height (58.46 cm), number of tillers per square meter (220 $tillers.m^{-2}$) and straw yield (882.29 $kg.ha^{-1}$) were obtained in the second ratoon cycle. Compared to the main crop, the height decreased by 19.02% and 31.37% in the first and second ratoon cycles, respectively. The decrease was clear for the number of tillers per m^2, with 14.66% in the 1st cycle, then 42.41% in the 2nd cycle of ratoons. Straw yield was the most affected, with a drop of 52.28% in the first cycle and up to 65.87% in the second ratoon cycle (Table 2).

Table 1. *Plant height, number of tillers and straw yield of NERICA L14 rice according to the cropping cycle.*

Cropping cycle	Plant height (cm)	Number of tillers per square meter	Straw yield ($kg.ha^{-1}$)
Main crop	85.18 ±6.42 a	382 ±89 a	2,584.82 ±361.73 a
1st ratoon cycle	68.98 ±3.74 b	326 ±41 b	1,233.54 ±279.05 b
2nd ratoon cycle	58.46 ±4.95 c	220 ±36 c	882.29 ±226.60 c
Mean	70.87 ±5.04	309 ±55	1,566.88 ±289.13
p-value	< 0.0001	< 0.0001	< 0.0001

In the table, values (±standard deviation) followed by the same letters within a column are not significantly different at the 5% level according to the Dunn's test (Post hoc Kruskal-Wallis).

Table 2. Increment rate of plant height, number of tillers and straw yield of NERICA L14 rice ratoon cycles compared to the main crop.

Cropping cycle	Increment rate (%)		
	Plant height	Number of tillers per square meter	Straw yield
Main crop	-	-	-
1st ratoon cycle	- 19.02	- 14.66	- 52.28
2nd ratoon cycle	- 31.37	- 42.41	- 65.87

In the table, negative values (-) correspond to reductions in the height, number of tillers and straw yield of the ratoons, respectively.

3.2. Effect of Mineral Fertilization on Rice Ratoon Plant Height

Mineral fertilization applied to ratoon crops of NERICA L14 rice had a significant effect on plant height across the two cycles ($P < 0.05$). Plant height ranged from 66.28 to 73.15 cm in the first ratoon generation and from 50.9 to 65.05 cm in the second (Figure 2). A significant reduction was observed between the first and second ratoon cycles, varying from 9.24% to 23.20% depending on the mineral fertilizer applied (Table 3). In the first ratoon cycle, nitrogen (73.15 cm), potassium (71.6 cm), and, to a lesser extent, zinc (70.6 cm) produced the highest plant heights. The corresponding increases about the unfertilized control were 8.61%, 6.31%, and 4.82%, respectively. Conversely, calcium (66.28 cm), phosphorus (66.5 cm), and, to a lesser extent, control (67.35 cm) resulted in the lowest heights, with reductions of 1.59% for Ca and 1.26% for P compared to the control. In the second ratoon cycle, nitrogen (65.05 cm) again promoted the highest plant height, representing a 6.24% increase compared with the control. In contrast, potassium (59.08 cm), zinc (61.88 cm), and magnesium (56.55 cm) produced plant heights that were statistically like the control (61.13 cm), with relative increment ranging from -7.49% to +1.22%. Calcium (50.9 cm) and, to a lesser extent, phosphorus (54.65 cm) induced the lowest values, corresponding to decreases of 16.73% and 10.60%, respectively, compared with the control.

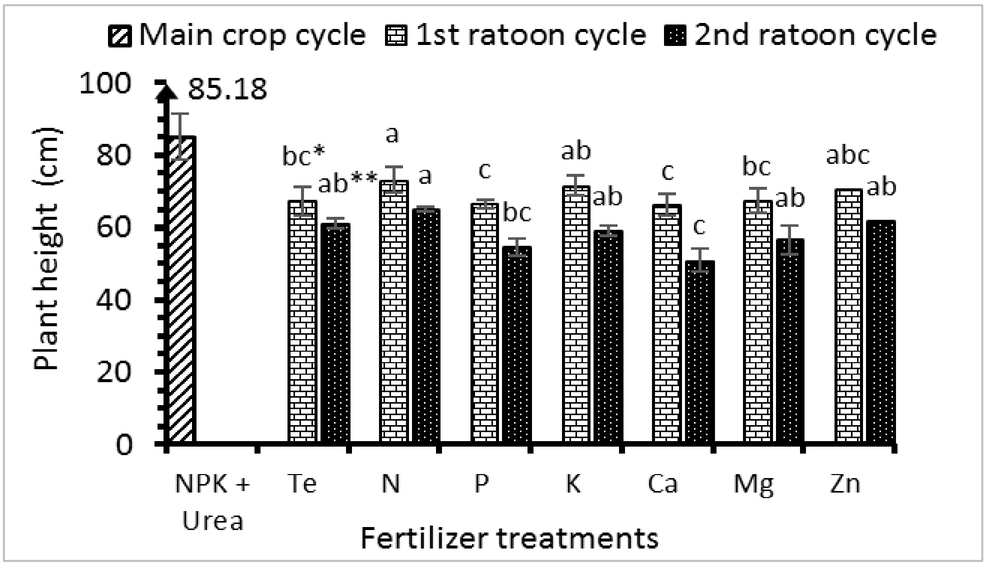

Figure 2. Mean heights of NERICA L14 rice ratoons as a function of fertilizer treatments and cropping cycle.

* For the 1st ratoon cycle, mean bars (±standard deviation) followed by different letters are significantly different at the 5% level according to the Duncan's test (post hoc ANOVA).
** For the 2nd ratoon cycle the histogram, mean bars (±standard deviation) followed by different letters are significantly different at the 5% level according to the Dunn's test (post hoc Kruskal-Wallis).

Table 3. *Increment rates of NERICA L14 rice ratoon height on the control and cropping cycle, according to the mineral fertilizers.*

Fertilizer treatments	**Increment rates of plant height (%)**		
	1st ratoon cycle	**2nd ratoon cycle**	**1st to 2nd ratoon cycle**
Te	-	-	-9.24
N	+ 8.61	+ 6.41	- 11.07
P	- 1.26	- 10.60	- 17.82
K	+ 6.31	- 3.35	- 17.49
Ca	- 1.59	- 16.73	- 23.20
Mg	+ 0.07	- 7.49	- 16.10
Zn	+ 4.82	+ 1.22	- 12.35

In the table, negative (−) and positive (+) values correspond, respectively, to reductions and increases in ratoon plant height.

3.3. Effect of Mineral Fertilization on Rice Plant Number of Tillers

The practice of two successive ratoon cycles combined with the application of mineral fertilizers had significant effects on the number of tillers per square meter in NERICA L14 rice (Table 4). In the first ratoon cycle, the highest tillering capacities were observed under magnesium, nitrogen, zinc, and potassium applications, with mean values of 366 tillers.m^{-2}, 354 tillers.m^{-2}, 343 tillers.m^{-2}, and 336 tillers.m^{-2}, respectively. The corresponding tillering increment rates were 10.16%, 12.46%, 16.06%, and 20.00% for K, Zn, N, and Mg, respectively (Table 5). Conversely, the lowest tiller number (263 tillers.m^{-2}) was recorded under the application of calcium, representing a 13.77% decrease compared to the control. In the second ratoon cycle, nitrogen (256 tillers.m^{-2}), phosphorus (249 tillers.m^{-2}), and zinc (241 tillers.m^{-2}) induced the highest tiller numbers, improving tillering by 37.63%, 33.87%, and 29.57% compared with the control. The lowest tiller numbers were observed in plots treated with magnesium (175 tillers.m^{-2}), in the control plots (186 tillers.m^{-2}), and in those treated with calcium (202 tillers.m^{-2}). Compared to the control, the tillering increment rates were -5.91% for Mg and +8.60% for Ca. The cumulative results of the number of tillers per square meter across both ratoon cycles indicated the highest averages in plots fertilized with nitrogen (611 tillers.m^{-2}) and zinc (584 tillers.m^{-2}). In contrast, calcium treated plot and the unfertilized control produced the lowest values, with 465 and 491 tillers.m^{-2}, respectively.

Table 4. *Number of tillers per square meter in NERICA L14 rice ratoons as a function of fertilizer treatments and cropping cycle.*

Fertilizer treatments	**Number of tillers per square meter**		
	1st ratoon cycle	**2nd ratoon cycle**	**1st + 2nd ratoon cycle**
Te	305 ±8 c *	186 ±3 c **	491 ±9 c *
N	354 ±13 ab	256 ±33 a	611 ±30 a
P	313 ±22 bc	249 ±14 a	563 ±11 b
K	336 ±41 abc	229 ±27 abc	565 ±45 b
Ca	263 ±24 d	202 ±24 bc	465 ±20 c
Mg	366 ±34 a	175 ±26 c	542 ±18 b
Zn	343 ±36 abc	241 ±5 ab	584 ±35 ab
Mean	326 ±25	220 ±19	546 ±24
Pr > F or p-value	0.001	0.003	< 0.0001

Fertilizer treatments	Number of tillers per square meter		
	1st ratoon cycle	2nd ratoon cycle	1st + 2nd ratoon cycle
Fertilizer treatments	Main crop cycle		
NPK + Urea	382 ±89		

* For the 1st ratoon cycle and 1st + 2nd ratoon cycle, values (± standard deviation) followed by the same letters within a same column are significantly different at the 5% level according to the Duncan's test (post hoc ANOVA).
** For the 2nd ratoon cycle, values (±standard deviation) followed by the same letters are significantly different at the 5% level according to the Dunn's test (post hoc Kruskal-Wallis).

Table 5. *Increment rates of tiller number in NERICA L14 rice ratoons on the control, according to the mineral fertilizers and cropping cycle.*

Fertilizer treatments	Increment rates of the number of tillers (%)		
	1st ratoon cycle	2nd ratoon cycle	1st + 2nd ratoon cycle
Te	-	-	-
N	+ 16.06	+ 37.63	+ 24.44
P	+ 2.62	+ 33.87	+ 14.66
K	+ 10.16	+ 23.12	+ 15.07
Ca	- 13.77	+ 8.60	- 5.30
Mg	+ 20.00	-5.91	+ 10.39
Zn	+ 12.46	+ 29.57	+ 18.94

In the table, negative (−) and positive (+) values correspond, respectively, to reductions and increases in the number of tillers.

3.4. Effect of Mineral Fertilization on Rice Straw Yields

The effects of mineral fertilizers across the two successive ratoon cycles on straw yield are presented in table 6 and were significant. In the first ratoon generation, the highest straw yield was obtained under nitrogen fertilization, with 1,656.25 $kg.ha^{-1}$ compared to 1,291.75 $kg.ha^{-1}$ for the control, corresponding to an increment rate of 28.22% (Table 7). Straw yield (SY) values obtained under the other fertilizer treatments (1,000 to 1,312.5 $kg.ha^{-1}$) were statistically like the control. Phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K) all contributed to reductions in SY compared to the control, with respective decreases of 22.59%, 20.22%, 15.33%, and 3.23%. In contrast, zinc (Zn) induced only a slight increase of 1.61%. In the second ratoon generation, SY ranged from 668.81 to 1,242.19 $kg.ha^{-1}$. Compared with the control, all mineral fertilizers enhanced straw production by at least 12.14%. However, the highest SY was again obtained with nitrogen fertilization, yielding 1,242.19 $kg.ha^{-1}$ against 668.81 $kg.ha^{-1}$ for the control (the lowest mean value). This corresponded to a remarkable increment rate of 85.73%. Over the two successive ratoon cycles, nitrogen fertilized plots produced the highest cumulative SY, with 2,898.44 $kg.ha^{-1}$ compared with 1,960.56 $kg.ha^{-1}$ for the control, representing an increase of 47.84%. Yields obtained under zinc (2,296.88 $kg.ha^{-1}$), potassium (2,187.5 $kg.ha^{-1}$), and calcium (1,914.06 $kg.ha^{-1}$) were statistically like the control. In contrast, ratoon plots treated with phosphorus and magnesium recorded the lowest cumulative straw yields, with 1,750 $kg.ha^{-1}$ and 1,803.38 $kg.ha^{-1}$, corresponding to decreases of 10.74% and 8.02%, respectively. The duration of the main crop was 90 days, while each ratoon cycle lasted 45 days. Thus, the two successive ratoon generations covered 90 days.

Table 6. *Straw yields of NERICA L14 rice ratoons as a function of fertilizer treatments and cropping cycles.*

Fertilizer treatments	**Straw yields (SY) in kg.ha^{-1}**		
	1st ratoon cycle	**2nd ratoon cycle**	**1st + 2nd ratoon cycle**
Te	1,291.75 ± 10.24 b *	668.81 ± 7.68 b **	1,960.56 ± 17.93 ab **
N	1,656.25 ± 257.69 a	1,242.19 ± 193.27 a	2,898.44 ± 450.96 a
P	1,000.00 ± 0.00 b	750.00 ± 0.00 ab	1,750.00 ± 0.00 b
K	1,250.00 ± 0.00 b	937.50 ± 0.00 ab	2,187.50 ± 0.00 ab
Ca	1,093.75 ± 62.5 b	820.31 ± 46.88 ab	1,914.06 ± 109.38 ab
Mg	1,030.50 ± 35.3 b	772.88 ± 26.42 ab	1,803.38 ± 61.65 b
Zn	1,312.50 ± 473.24 b	984.38 ± 354.93 ab	2,296.88 ± 828.17 ab
Mean	1,233.54 ± 119.84	882.30 ± 89.88	2,115.83 ± 209.73
Pr > F or p-value	0.003	0.001	0.005
Fertilizer treatments	Main crop cycle		
NPK + Urea	2,584.82 ± 361.73		

* For the 1st ratoon cycle, values (± standard deviation) followed by the same letters are significantly different at the 5% level according to the Duncan's test (post hoc ANOVA).
** For the 2nd ratoon cycle and 1st + 2nd ratoon cycle, values (± standard deviation) followed by the same letters within a same column are significantly different at the 5% level according to the Dunn's test (post hoc Kruskal-Wallis).

Table 7. *Increment rates of straw yield in NERICA L14 rice ratoons on the control, according to the mineral fertilizers and cropping cycles.*

Fertilizer treatments	**Increment rates of straw yields (%)**		
	1st ratoon cycle	**2nd ratoon cycle**	**1st + 2nd ratoon cycle**
Te	-	-	-
N	+ 16.06	+ 37.63	+ 24.44
P	+ 2.62	+ 33.87	+ 14.66
K	+ 10.16	+ 23.12	+ 15.07
Ca	- 13.77	+ 8.60	- 5.30
Mg	+ 20.00	-5.91	+ 10.39
Zn	+ 12.46	+ 29.57	+ 18.94

In the table, negative (−) and positive (+) values correspond, respectively, to reductions and increases in straw yield.

4. Discussion

Our analyses revealed that growth parameters (plant height and number of tillers per square meter) and straw yield of NERICA L14 rice ratoons declined from the first to the second cycle. These observations are consistent with those reported by Dossou-Yovo et al. [17] and Faruq et al. [30], who demonstrated the depressive effect of successive ratoon cycles on vegetative growth and yields in Ivory Coast and Senegal. Consequently, yield appears to decrease progressively with an increasing number of ratoon cycles. This trend may be explained by the slowing of metabolic activity in ratoon plant cells, including roots, which approach senescence as cycles succeed one another, leading to reduced water and nutrient uptake [31]. Additionally, shorter growth duration observed in successive ratoon crops could contribute to these results, as confirmed in previous studies on rice [32, 33].

These outcomes may also be related to increasing imbalances in soil mineral elements with successive ratoon cycles, despite fertilization. Such imbalances arise from high nutrient uptake by the main crop [26]. Effective mineral nutrition for plants, including ratoons, requires a balanced supply of all essential elements rather than the application of a single nutrient [34].

The application of different fertilizers during ratoon cropping significantly affected plant height, tillering, and consequently straw yield, compared to control elementary plot for each cycle. These results underscore the importance of fertilization in rice cultivation, as highlighted by Saidou et al. [10]. The enhanced vegetative growth and straw yield observed under nitrogen (N), zinc (Zn), and potassium (K) applications align with the findings of Kouakou et al. [19], who emphasised the positive effects of these minerals on growth, yield, and ratooning capacity of NERICA L14. Recent studies have demonstrated the direct impact of N on plant height, tiller number, and ratoon architecture [27, 35]. Nitrogen promotes vegetative production [25], being the most limiting nutrient in rice cultivation; it is essential for chlorophyll synthesis, key for photosynthesis [36], and for enzymes involved in general plant metabolism. In rice, N stimulates active vegetative growth of young organs by increasing plant height, leaf size, and tiller number [37]. The positive effect of Zn on straw yield can be attributed to its role in enhancing tillering (by 5–14.2%), mineral nutrition, and growth. Zn participates in nitrogen and auxin metabolism, chlorophyll synthesis [38], and the uptake, translocation, and distribution of N and P in ratoons. Efficient phosphorus assimilation, in turn, promotes root growth, tillering, and recovery after stress [39]. Similar findings were reported by Tuiwong et al. [40] and Ji et al. [41], showing significant improvements in tiller number and length, total yield (including straw), and biomass following the application of Zn. Moreover, Zn enhances soil nitrogen transformation through increased total N availability, enzymatic activity, and microbial community modulation, thereby improving nitrogen nutrition and rice growth [42]. Concerning K, our results demonstrated that it similarly improved plant height, tillering, and straw yield, consistent with the findings of Kouakou et al. [22] under NERICA L14 fertilization. This effect is explained by potassium promotion of tillering, stomatal regulation, osmolyte balance, and energy equilibrium, which enhance resistance to drought, cold, lodging, and osmotic stress, while improving water retention. Recent studies indicate that K application stimulates root length and density, organic acid secretion, and soil microbial diversity, thereby strengthening growth under water stress and reducing disease and pest incidence [43-45]. K also enhances the plant's response to phosphorus (P), enabling balanced mineral nutrition and improving both grain and straw yields [46]. The depressive effect of calcium (Ca) on vegetative growth and straw yield in each ratoon cycle may result from the plant's low requirement for this element [47]. Moreover, excessive Ca assimilation increases cell membrane rigidity, limiting cell expansion [48], thereby reducing biomass accumulation and straw yield.

In the main crop of NERICA L14, from which the ratoons originated, the study recorded a 90-day cycle, an average tiller number of 382 per m^2, and a straw yield of approximately 2,585 $kg.ha^{-1}$ [19]. With a 45-day cycle per ratoon, two successive cycles (90 days) with nitrogen as the sole fertilizer resulted in a cumulative straw yield of 2,898 $kg.ha^{-1}$, significantly higher than that of the main crop. This confirms that ratoon cropping is an effective strategy to increase rice straw production while reducing production time, costs, and efforts. Nitrogen (N) and to a lesser extent zinc (Zn) and potassium (K) can therefore be recommended for enhancing straw yield in NERICA L14 ratoon cropping.

5. Conclusions

The ratoon crop induces an increasingly significant decline in growth and straw yield of NERICA L14 rice in each cycle, despite the application of fertilizers. This research shows that the main crop is the cycle in which the agronomic potential of NERICA L14 is best expressed. However, over the two successive ratoon cycles, the number of tillers, regardless of treatment, and straw yields under the effect of some mineral fertilizers were significantly higher than those of a new main crop. The cultivation of two successive ratoon cycles is therefore a good option for increasing the yields (particularly straw) of NERICA L14 rice. Our results showed, in general, better utilization of nitrogen (N), zinc (Zn), and, to a lesser extent, potassium (K) in ratoon crops, leading to good vegetative growth and, consequently, excellent straw yield for NERICA L14. On the other hand, calcium (Ca) harmed height, number of tillers and SY in ratoon crops. Thus, compound fertilizers containing nitrogen (N), zinc (Zn), and potassium (K) could be recommended to improve the growth and straw yield of ratoon crops. Their application would help to increase the biomass production of NERICA L14 rice in Ivory Coast at a lower cost, with less effort and in a short time.

Abbreviations

NERICA L14	New Rice for Africa Lowland 14
SY	Straw Yields
ANOVA	Analysis of Variance

Acknowledgments

We are grateful to Dr. Sitapha DIATTA at Africa Rice station of Bouake, in Ivory Coast for providing us with NERICA L 14 seeds.

Author Contributions

Kouakou Olivier Konan: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing

Kouadio Edouard Yves Gilchrist: Data curation, Formal Analysis, Methodology, Software, Writing – original draft, Writing – review & editing

Kone Brahima: Formal Analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing

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Funding

This work is not supported by any external funding.

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Kouakou Olivier Konan: Plant Physiology, Plant nutrition, Pedology, Riz ratooning, life and earth sciences

Kouadio Edouard Yves Gilchrist: Plant Physiology, Plant pathology and parasitic nematodes, Plant protection, Pesticides tests and homologation, Field experimentation, Banana cultivation

Kone Brahima: Pedology, Fertilization, Rice nutrition and cultivation, Biometrics, Riz selection, climate change, Modeling

Otron Houa Daniel: Plant virology, Biotechnology, Bioinformatic, Molecular Biology, Biometrics, Cassava

Dick Acka Emmanuel: Plant Physiology, Fruit and Legumes post-harvest, Improving crop production, Banana, Pineapple