Research Article

Balanced Fertilization Optimizes Nutrient Efficiency in Rice (*Oryza sativa* L.) Grown Under Sodic Soil Conditions

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Abstract | Mineral nutrition plays a determining role in the production of rice crops (O*ryza sativa* L.). In order to determine a balanced fertilization scheme that optimizes the efficient use of nutrients in rice under sodic soil conditions, five fertilization programs (FP) were evaluated in two varieties of rice (INIAP 11 and INIAP 14), with increasing nutrient doses (kg ha^{-1}): FP1 (N, 35; P, 3.3; K, 6.3; Ca, 40; Mg, 18); FP2 (N, 70; P, 6.6; K, 12.5; Ca, 80; Mg, 36); FP3 (N, 105; P, 9.8; K, 18.8; Ca, 120; Mg, 54); FP4 (N, 140; P, 13.1; K, 25; Ca, 160; Mg, 73), and FP5 (N, 175; P, 16.4; K, 31.3; Ca, 200; Mg, 90), in addition to two controls without fertilization, in a randomized complete block design (RCBD). The results showed that plant height varied significantly depending on the variety and fertilization programs. Program FP3 favored the height growth of INIAP 11 plants, while for INIAP 14 programs FP3, FP4 and FP5 were more effective. The agronomic and nutrient recovery efficiency varied according to the programs, with FP3 standing out with the best results in both varieties. The agronomic and nutrient recovery efficiency influenced the growth and productive performance of the rice crop. In conclusion, the balanced contribution of nutrients in rice cultivation under sodic soil conditions can increase grain production by improving the efficient use and recovery of nutrients from the soil.

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Introduction

Rice is one of the most important crops in the world, considered the main source of calories for more than half of the world's population (Ding *et al*., 2018). Its economic importance lies in the enormous extension of cultivated area, which covers 163 million ha in the world (Shahane *et al*., 2019). This cereal is a basic food in most countries, due to the abundant supply of vitamins, minerals and polyphenols (Rathna *et al*., 2019). Rice production currently exceeds 700 million metric tons (MT), with China and India being the main producers (FAO, 2022). In Ecuador, there are 342,967 hectares of rice cultivated area, with a total production of 1,503,526 Mt (ESPAC, 2021).

Rice represents a basic food for many cultures around the world (Vinci *et al*., 2023). However, there are environmental conditions that substantially impair its production, such as soil salinity (Choudhury *et al*., 2018). Soil salinity affects ~ 10% of the world's arable surface, becoming a limitation for food exploitation (Mishra *et al*., 2023). Soils affected by salinity have reduced levels of organic matter, which results in low fertility (Choudhary and Yaduvanshi, 2016). The correct management of nutrients in this type of soil constitutes an appropriate measure for the sustainable maintenance of the rice cultivation productive system (Shrestha *et al*., 2020).

Since the green revolution, the intensive use of agricultural practices, including unbalanced fertilization, led to soil degradation, causing reductions in crop yields (Jat *et al*., 2018). In regions with arid and semi-arid soils, the of high contents of salts such as Mg^{2+}, Ca^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, CO_3^{2-} and HCO_3^- accumulated as a result of the low rainfall that prevents their washing (Choudhary and Yaduvanshi, 2016). Salinity and sodicity in the soil can reduce crop productivity (Mishra *et al*., 2023). Soils affected by salts often have low organic matter content, which translates into poor fertility (Choudhary and Yaduvanshi, 2016). The efficient use of nutrients constitutes an essential component in soil and plant management. Knowledge of the nutrients required at all stages of growth and understanding the soil's ability to provide the necessary nutrients are crucial for profitable crop production (Shrestha *et al*., 2020).

Rice cultivation is highly demanding of nutrients to achieve satisfactory yields (Thakur *et al*., 2020). Sixteen nutrients are considered important for rice, with N, P, and K being the primary macronutrients; Mg, Ca and S are secondary macronutrients; and Zn, Fe, Mn, Cu, B, Mo and Cl are micronutrients (Maathuis, 2009). Often, fertilizers are not applied in a balanced manner according to soil analysis criteria and crop requirements. Frequently, producers focus only on N application, which results in unbalanced fertilization (Shankar *et al*., 2021). Therefore, adequate nutrient management, in correspondence with the natural fertility of the soil, is key to maintaining sustainable yields and a nutritional balance of the soil (Shankar *et al*., 2021). Furthermore, inadequate fertilization practices can generate greenhouse gas emissions, such as N_2O, which can reach up to 60 % (Hasanuzzaman *et al*., 2012). Likewise, excess fertilization can have negative effects on soil nutrient dynamics of the soil (Hu *et al*., 2021). A recommended practice to minimize these drawbacks is to evaluate the efficient use of nutrients (Sai-Ram *et al*., 2020). It has been suggested that studies in this field allow the identification of genotypes and/or cultivars with a greater capacity to absorb and use nutrients, resulting in an increase in crop yields (Baligar *et al*., 2001).

Despite the growing interest in efficient nutrient use, existing studies are often based on the effect of nutrient application on rice yield. Some authors have evaluated the effect of chemical fertilization on rice productivity (Ding *et al*., 2018; Haque *et al*., 2019); however, research carried out in sodic soil conditions is scarce. The presence of sodium ions (Na^+) in the soil causes particle dispersion and lack of aggregate formation, resulting in poor aeration and slow water movement (O'Geen, 2018). Plants that use nutrients more efficiently represent greater income for producers and contribute to the sustainable management of natural resources (Puentes *et al*., 2016). Based on this background, the objective of this research was to evaluate the nutrient efficiency through different fertilization schemes in rice cultivation under sodic soil conditions.

Materials and Methods

Location

The research was carried out at the Horcón site in the Rocafuerte Canton, Manabí Province, Ecuador, at 00°52'57" S-80°29'10" W. The land presented flat topography and the soil had a clay loam texture. The chemical properties of the soil are presented in Table 1.

Table 1: *Soil chemical characteristics Soil chemical characteristics.*

pH	Organic matter	P	K^+	Ca^{2+}	Mg^{2+}	Na^+	CIC
	(%)	(mg kg^{-1})		(meq 100g^{-1})			
8.7	1.5	26	0.38	12	2.6	3.86	25.06
Slightly alkaline	Low	High	Medi-um	High	High	High	Good

Genetic material, treatments and trial management

The rice varieties INIAP 11 and INIAP 14, acquired from the National Autonomous Institute of Agricultural Research (INIAP), were used. Additionally, five fertilization programs (FP) were evaluated, with increasing doses of N, P, K, Ca and Mg. Two control treatments were included: INIAP 11 and INIAP 14, both without fertilization. The treatments were distributed in a randomized complete block design (RCBD). Each experimental unit had an area of 45 m^2. Table 2 details the configuration of the treatments based on the different study factors.

Table 2: *Factors under study to determine nutrient use in two rice varieties.*

Rice varieties	Fertilization programs (kg ha^{-1})
INIAP 11	1 (N= 35; P = 3.3; K= 6.3; Ca= 40; Mg= 18)
	2 (N= 70; P = 6.6; K= 12.5; Ca= 80; Mg= 36)
INIAP 14	3 (N= 105; P = 9.8; K= 18.8; Ca= 120; Mg= 54)
	4 (N= 140; P = 13.1; K= 25; Ca= 160; Mg= 73)
	5 (N= 175; P = 16.4; K= 31.3; Ca= 200; Mg= 90)

Control treatment 1: INIAP 11 without fertilization. Control treatment 2: INIAP 14 without fertilization.

The establishment of the seedbed was carried out simultaneously with the preparation of the land for the definitive transplant of the crop. The rice seeds were randomly distributed in the area intended for the seedbed. Subsequently, irrigation was carried out maintaining a permanent sheet of water above ground level. The plants remained in the seedbed for 22 days. Once the plants reached the appropriate age (22 days after sowing), they were transplanted at a distance of 25 cm between rows and 25 cm between plants, placing 15 plants per site. In this way, a density of 240 plants/m^2 was obtained, a population range within that suggested by Degiovanni *et al.* (2010). For pre-emergence control of grass and broadleaf weeds, Pendimentalin® (2 L ha^{-1}) and Butachlor® (3 L ha^{-1}) were applied, respectively. The flood irrigation method was used. Before the application of fertilizers and weed control, water was removed from the plots. Once these tasks were completed (8 days later), flooding was reestablished.

Fertilization was carried out according to the quantities established for each treatment (Table 2). Different sources of fertilizers were used; urea (N 46– P 0 – K 0), diammonium phosphate (N 18 – P 46 – K 0), potassium nitrate (N 13 – P 0 – K 45) and dolomite lime (CaO 35 %, MgO 16 %). The application of N, K, Ca and Mg was divided into three periods, corresponding to 25%, 35% and 40% at 8, 22 and 45 days after transplantation, respectively. In the case of P, 100 % of the requirement was applied on a single occasion, specifically eight days after the transplant.

Pest control was carried out through the application of Profenofos® (500 mL ha^{-1}), Abamectin® (300 mL ha^{-1}) and Diazinon® (500 mL ha^{-1}), while disease control was carried out with the application of Mancozeb® (1 kg ha^{-1}) and propiconazole+difenoconazole (Chispa®, Nanjing Essence, Nankin, China) at 250 mL ha^{-1}.

The harvest was carried out manually 100 days after transplanting, coinciding with the physiological maturity of the plants. The plants were cut with a sickle, followed by manual separation of the grain from the panicle.

The response variables in vegetative growth (height and length of roots, dry weight of roots and shoots) and reproductive (number of panicles/$plant^{-1}$, number of grains $panicle^{-1}$, weight of grains, and final yield (kg ha^{-1}) were measured. Additionally, the agronomic efficiency (AE) and the fertilizer recovery efficiency (FRE) were calculated, according to Baligar *et al.* (2001) using Equations 1 and 2:

$$AE = \frac{R(f) - R\ (t)}{NAF} kg\ kg^{-1} \quad ...(1)$$

Where; *R*(*f*) = Yield (grain 14% moisture) of the fertilized treatment. *R*(*t*) = Yield (grain 14% moisture) of the unfertilized treatment. NAF = Nutrient amount applied with the fertilizer.

$$FRE\ (\%) = \frac{EN(f) - EN(t)}{NA} x\ 100 \quad ...(2)$$

Where: *EN*(*f*)= Amount of nutrients (grains) in the fertilized treatments. *EN*(*t*)= Amount of nutrients (grains) in unfertilized treatment. NA=Nutrient applied through fertilizer.

To calculate the concentration of nutrients (GNC) in rice grains, a sample covering an area of 3 m^2 was extracted from each experimental unit. In these samples, N levels were determined using the Kjeldahl method, while for P the colorimetry method was used. For the elements K, Ca, Mg and Na, a previous digestion with 6 M HCl was carried out, followed by measurement by atomic absorption.

Data analysis
The data were submitted to tests for normality (Shapiro's test) and homogeneity of variances (Bartlett's test). Following the confirmation of these assumptions, an analysis of variance (ANOVA) was conducted. The adopted analytical framework consisted of a factorial using randomized blocks, which included two additional control groups (2x5 + 1+1; $y_{ijk} = \mu+\beta_i+\alpha_j+\tau_k+\alpha\tau_{jk}+\varepsilon_{ijk}$ and $y_h=\mu+\gamma_a+\varepsilon_h$). Multiple comparison analysis (Scott-Knott; $p \leq 0.05$) was performed when significant differences were detected in the ANOVA test. The Dunnett test was applied for comparing common treatments and additional treatments. For comparing two independent means, the t-student test was performed. Regression analysis was used to estimate the relationship between crop yield and fertilization programs. All statistical analyzes were achieved using the Tratamientos. Ad and Exp Des.pt packages available in R software (version 4.3.1) 2023 (R Core Team, 2023).

Results and Discussion

Vegetative growth variables
Plant height was notably influenced by the type of cultivar (p=0.001), as well as by the fertilization programs, FPs (p<0.001). Treatment FP3 promoted the greatest growth in plant height of the INIAP 11 cultivar (102.00 cm), followed by FP4, FP2, FP5 and FP1 with plant heights of 98.6, 95.3, 87.3 and 83.3 cm, respectively, being different from the unfertilized control with a height of 76.6 cm (Figure 1). In the case of the INIAP 14 cultivar, a greater height was observed in the plants that received fertilization with FP3, FP4 and FP5, presenting a mean height of 95.0 cm, higher than the FP2 and FP1 treatments with a height of 89.0 and 82.6 cm, respectively, while the control without receiving fertilization reached a height of just 76.0 cm.

In relation to root length, the different FPs influenced root growth, with significant differences (p<0.001) being observed between treatments. In the INIAP 11 cultivar, plants fertilized with FP3 showed a mean root length of 36.3 cm, while the rest of the treatments (FP1, FP2, FP4 and PF5) showed a mean root length of 31.0 cm. All FPs were higher than the control treatment (26.0 cm). In the INIAP 14 cultivar, the plants treated with the different FPs were not different from each other, showing mean root length of 30.8 cm, but they were different from the control treatment (25.6 cm).

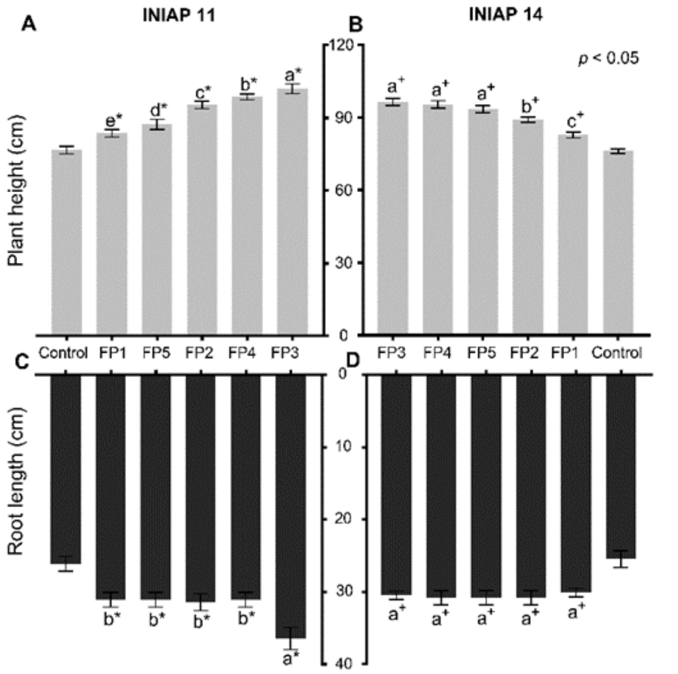

Figure 1: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions on vegetative growth characteristics. (A-B) Plant height and (C-D) Root length. Fertilization programs based on increasing nutrients of N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Bars with the same letters are statistically similar according to the Scott-Knott´s test (p≤0.05). Bars follow by * and + indicate statistical differences between common treatments and controls according to the Dunnett´s test (p≤0.05). Error bars represent the standard error of the mean.*

The dry weight of shoots was significantly influenced by the effect of the cultivars (p<0.001) and the different FPs (p<0.001). Plants of INIAP 11 under FP3 had the highest dry weight of shoots (761.3 g), followed by FP4 (578.0 g), while the FP5 and FP2 treatments showed a mean of 570.0 g. Finally, FP1 presented the lowest dry weight of shoots with 431.3 g. All treatments were statistically superior to the control treatment (376.3 g). In the INIAP 14 cultivar, the dry weight of shoots increased according to the following order: FP3 > FP4 > FP5 > FP2 > FP1, with mean weights of 676.6, 608.3, 585.6, 548.0 and 436.0 g, respectively, all of these being higher than the control treatment, presenting only 361.6 g (Figure 2A-B).

The dry weight of roots was also significantly different due to the effect of the cultivar (p<0.001) and the FPs (p<0.001). The INIAP 11 cultivar treated with FP3 showed 257.6 g of dry weight of roots, higher than the FP4 treatment with a mean of 229.6 g. In turn, plants treated with FP5 and FP2 showed a mean of 198.4 g. Finally, dry weight of roots in FP1 was 144.0 g. Meanwhile, in the INIAP 14 cultivar, the dry weight of roots was higher in plants treated with FP3, in which a mean of 229.0 g, followed by FP4 and FP5 with a mean weight of 205.3 g, respectively, were found, whereas FP2 and FP1 showed the lowest values of root dry weight with 185.0 and 147.3 g, respectively. The dry weight of roots of the control treatment was only 122.0 g (Figure 2C-D).

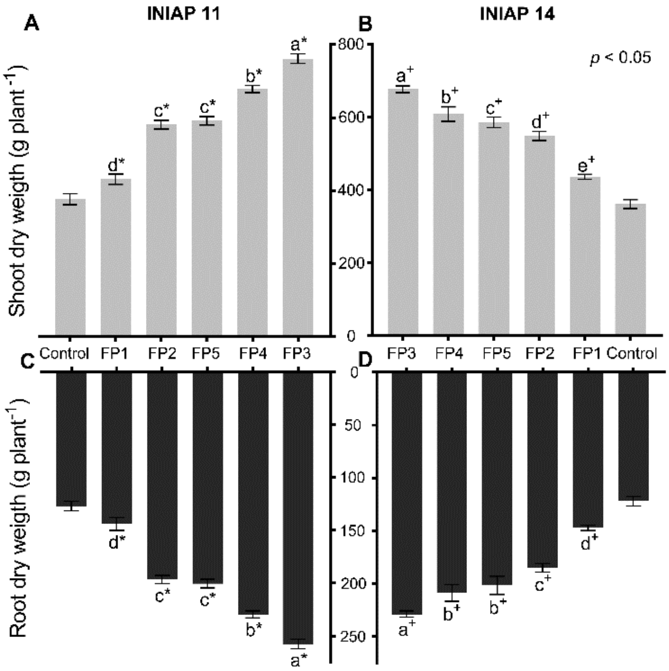

Figure 2: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions on vegetative growth characteristics. (A-B) Shoot dry weight and (C-D) Root dry weight. Fertilization programs based on increasing nutrients of N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Bars with the same letters are statistically similar according to the Scott-Knott's test (p≤0.05). Bars follow by * and ⁺ indicate statistical differences between common treatments and controls according to the Dunnett's test (p≤0.05). Error bars represent the standard error of the mean.*

Concentration of nutrients in grain

Grain nutrient levels were significantly influenced by the effect of FPs (p<0.001). The highest concentration of N in the grains was recorded at 24.3 g kg^{-1} for the INIAP 11 cultivar and 22.3 g kg^{-1} for the INIAP 14 cultivar under FP3. Intermediate values were observed in FP2 (20.6 g kg^{-1}) and FP4 (20.5 g kg^{-1}) for the INIAP 11 and INIAP 14 varieties, respectively. The lowest concentrations occurred under FP1 (18.9 g kg^{-1}) and FP5 (18.8 g kg^{-1}). The control treatments showed lower N concentration in grain for both cultivars, with a mean of 17.3 g kg^{-1} (Figure 3A).

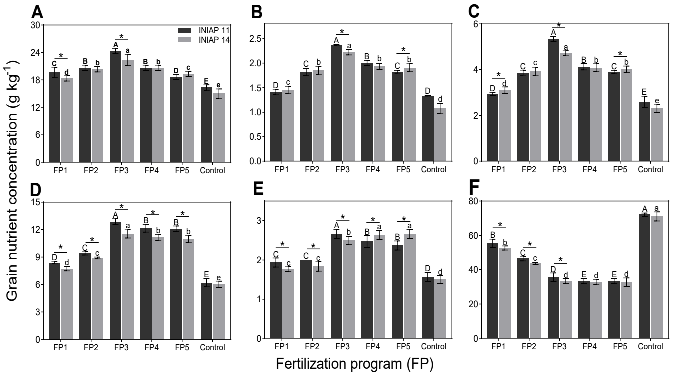

Figure 3: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions on nutrient concentrations (g kg^{-1}) in grain. (A) Nitrogen, (B) Phosphorus, (C) Potassium, (D) Calcium, (E) Magnesium (Mg), and (F) Sodium concentration. Fertilization programs based on increasing nutrients of N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Bars with the same letters are statistically similar according to the Scott-Knott's test (p ≤ 0.05). Asterisks (*) indicate a statistical difference between cultivars according to the t-Student test (p≤0.05). Error bars represent the standard error of the mean.*

The concentration of P in grain was higher with the application of FP3, reaching values of 2.3 and 2.2 g kg^{-1} in the INIAP 11 and INIAP 14 cultivars, respectively. Intermediate values were found in FP4, FP5 and FP2, with mean concentrations of 1.9 g kg^{-1} (INIAP 11) and 1.9 g kg^{-1} (INIAP 14). The lowest concentrations were presented in PF1 with 1.41 and 1.46 g kg^{-1} for the INIAP 11 and INIAP 14 cultivars, respectively (Figure 3B).

In relation to K, the highest concentration in grain was observed in FP3, with values of 5.34 and 4.71 g kg^{-1} in INIAP 11 and INIAP 14, respectively. Intermediate values were reported for FP4, FP5 and FP2, with mean values of 3.9 g kg^{-1} (INIAP 11) and 4.0 g kg^{-1} (INIAP 14). The lowest K concentrations occurred in FP1 with 2.9 g kg^{-1} in INIAP 11 and 3.1 g kg^{-1} in INIAP 14 (Figure 3C).

Likewise, the highest concentration of Ca in grain was evident through the application of FP3, reaching 12.8 and 11.5 g kg $^{-1}$ in the INIAP 11 and INIAP 14 cultivars, respectively. Intermediate responses were promoted by FP4 and FP5 with a mean grain Ca concentration of 12.1 and 11.1 g kg $^{-1}$ for the INIAP 11 and INIAP 14 cultivars, respectively, while FP1 and FP2 showed the lowest values with 8.9 and 8.3 g kg $^{-1}$ in the INIAP 11 and INIAP 14 cultivars, respectively (Figure 3D).

The concentration of Mg in grain was higher with FP3 in the INIAP 11 cultivar (2.66 g kg^{-1}), while in INIAP 14, the highest levels of Mg in grain were observed with FP4 and FP5, with a mean of 2.6 g kg^{-1}. Intermediate levels of Mg concentration in grain were found in the INIAP 11 cultivar treated with FP4 and FP5, showing a mean of 2.4 g kg^{-1}. In INIAP 14 intermediate values of Mg concentration were observed in FP3 with 2.5 g kg^{-1}. Grain Mg concentrations were lower in FP1 and FP2 with means of 1.9 and 1.8 g kg^{-1}, respectively (Figure 3E).

The Na content in the grain was greatly affected by the contributions of the different FPs. The Na content decreased as the nutrient supply increased. Thus, the lowest Na concentrations were in the FP4 and FP5 treatments with means of 33.3 and 32.7 g kg^{-1} for the INIAP 11 and INIAP 14 cultivars, respectively, while the control treatments reached the highest levels of Na in the grain with 72 and 71 g kg^{-1}, respectively (Figure 3F). The study of the relationship between Na concentration and CaO application showed that increasing CaO contributions reduced Na concentrations in the grains, which was verified through regression analysis (Figure 4).

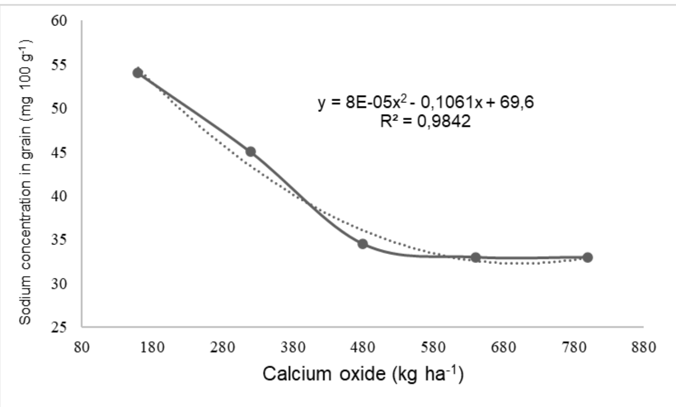

Figure 4: *Relationship between sodium concentration in rice grains and liming application levels (average of two rice cultivars).*

Agronomic nutrient efficiency

The AE of nutrients was significantly different (p<0.001) for all mineral elements and varied according to the FPs applied. The AE of N was higher under FP3, achieving 45.9 kg ha^{-1} of dry grain in the INIAP 11 cultivar and 37.5 kg ha^{-1} of dry grain in the INIAP 14 cultivar for each kg of N applied. The lowest values of AE were observed in FP5 with means of 15.4 and 16.0 kg ha^{-1} for the INIAP 11 and INIAP 14 cultivars, respectively (Figure 5).

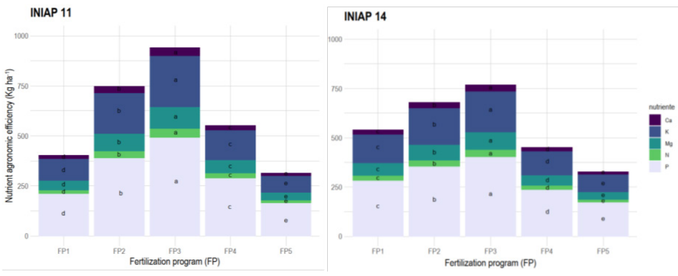

Figure 5: *Agronomic nutrient efficiency (kg ha^{-1}) with the application of different fertilization programs (FP) in two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions. Fertilization programs based on increasing nutrients of N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Letters that are the same color on the bars are statistically similar according to the Scott-Knott´s test (p≤0.05).*

The AE of P was statistically higher (p<0.001) in plants treated with FP3, presenting means of 491.2 and 401.7 kg ha^{-1} of dry grain in the INIAP 11 and INIAP 14 cultivars, respectively, for each kg of P applied. On the contrary, the lowest AE of P was exhibited by FP5 with means of 164.24 kg ha^{-1} in INIAP 11 and 170.91 kg ha^{-1} in INIAP 14 (Figure 5).

In relation to K, the highest agronomic efficiency was presented by the INIAP 11 variety, where each kilogram of K applied generated 161.7 kg of dry grain ha^{-1}, different from INIAP 14 with 151.3 kg of dry grain ha^{-1}. Treatment FP3 showed greater AE with 256.06 kg ha^{-1} (INIAP 11) and 209.41 kg ha^{-1} (INIAP 14). The lowest AE of K was observed in FP5 with means of 86.1 and 89.6 kg ha^{-1} in the INIAP 11 and INIAP 14 cultivars, respectively (Figure 5).

The greatest AE of Ca was shown by INIAP 11 (25.30 kg of dry grain ha^{-1}), higher than INIAP 14 (23.70 kg of dry grain ha^{-1}). In relation to the fertilization program, FP3 presented an efficiency of 40.11 and 32.80 kg ha^{-1} in the INIAP 11 and INIAP 14 cultivars, respectively. The lowest AE values were observed in FP5 with means of 13.46 kg ha^{-1} in INIAP 11 and 14.01 kg ha^{-1} in INIAP 14 (Figure 5).

The agronomic efficiency of Mg was greater in the INIAP 11 cultivar (67.5 kg of dry grains ha^{-1}), compared to INIAP 14 (63.2 kg of dry grains ha^{-1}). When FP3 was applied, AE of Mg was 106.9 and 87.5 kgha^{-1} for the INIAP 11 and INIAP 14 cultivars, respectively. On the contrary, the lowest AE was observed in FP5, presenting means of 35.9 in INIAP 11 and 37.4 kg ha^{-1} in INIAP 14 (Figure 5).

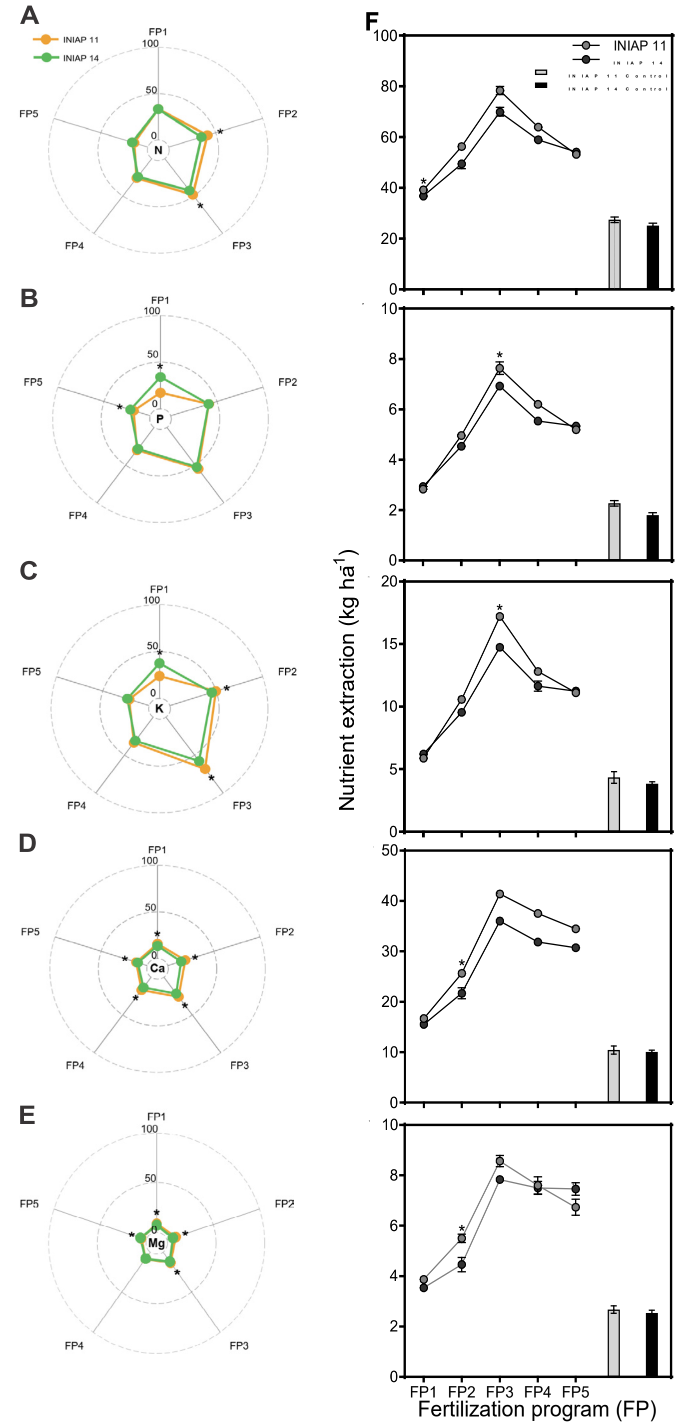

Figure 6: *Fertilizer recovery efficiency (%) (A-E) and nutrient extraction (Kg ha-1) (F-J) with the application of different fertilization programs (FP) in two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions. Fertilization programs based on increasing nutrients of N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Asterisks (*) indicate statistical differences between both cultivars according to the t-Student test (p≤0.05). Error bars represent the standard error of the mean.*

Fertilizer recovery efficiency

Fertilizer recovery efficiency for N was significantly different due to the effect of cultivars (p=0.0013) and fertilization programs (p<0.001). The INIAP 11 cultivar presented higher FRE (32.8%) compared to INIAP 14 (30.3%). Plants treated with FP2 presented a FRE of 41.2 (INIAP 11) and 34.8% (INIAP 14), being different from each other. Similarly, with the application of FP3, FRE was 48.5% in INIAP 11 v. INIAP 14 with 42.60%. The lowest FRE was observed in INIAP 11 (14.69%) and INIAP 14 (16.61%) under FP5 (Figure 6A).

Phosphorus recovery efficiency was significantly influenced by both the cultivar (p<0.01) and the FPs (p<0.01). The INIAP 11 cultivar presented a FRE for P of 35.5%, while INIAP 14 showed a mean of 32.3%. The greatest P FRE was observed under FP3 with a mean of 54.96 (INIAP 11) and 52.5 % (INIAP 14). The lowest P FRE values were observed in FP1 (mean=17.2%; INIAP 11) and FP5 (mean=21.2; INIAP 14) (Figure 6B).

Potassium recovery efficiency was significantly affected by the effect of FPs (p<0.001). The K recovery efficiency was higher in FP3 with means of 68.3 (INIAP 11) and 57.8 % (INIAP 14). The lowest values were shown under FP5, exhibiting means of 21.5 and 23. % in INIAP 11 and INIAP 14, respectively (Figure 6C).

The FRE of Ca was affected by both the cultivar (p< 0.001) and the FPs (p<0.001). The greatest FRE of Ca was observed under FP3 in both the INIAP 11 (25.8%) and INIAP 14 (21.7%) cultivars. On the contrary, the lowest Ca FRE was presented under FP5, showing a mean of 11.2% for both cultivars (Figure 6D).

Finally, the Mg FRE presented significant differences between cultivars (p<0.001) and between FPs (p<0.001). The FRE for Mg was higher in FP3, with values of 13.2 and 11.8% in INIAP 11 and INIAP 14, respectively. The lowest Mg FRE was shown with the application of FP5 and FP2 in INIAP 11 (5.5%) and INIAP 14 (6.50%) (Figure 6E).

Nutrient extraction

The extraction of all nutrients was significantly influenced by the effect of cultivars (p<0.001) and FPs (p<0.001). The extraction of N, P, K, Ca and Mg improved as the nutrient supply increased in both cultivars.

Extraction of N in the INIAP 11 cultivar was 58.2

kg ha^{-1}, statistically higher than INIAP 14 with 53.8 kg ha^{-1}. The FP3 presented the highest level of N extraction with 78.3 (INIAP 11) and 63.8 kg ha^{-1} (INIAP 14) (Figure 6F). In relation to P, the INIAP 11 cultivar (5.4 kg ha^{-1}) presented higher extraction levels than INIAP 14 (5.1 kg ha^{-1}). The P extraction capacity was higher in plants treated with FP3, showing mean values of 7.6 and 6.9 kg ha^{-1} for INIAP 11 and INIAP 14, respectively (Figure 6G). On the other hand, the K extraction capacity was higher in the INIAP 11 cultivar (11.5 kg ha^{-1}) compared to INIAP 14 (10.7 kg ha^{-1}). This mineral was mostly extracted in plants treated with FP3, exhibiting means of 17.2 (INIAP 11) and 14.7 kg ha^{-1} (INIAP 14) (Figure 6H). In the case of Ca, the extractive capacity was greater in INIAP 11 (31.2 kg ha^{-1}) compared to INIAP 14 (27.2 kg ha^{-1}). Calcium was mostly extracted under the application of FP3 with means of 41.4 and 36.1 kg ha^{-1} in the INIAP 11 and INIAP 14 cultivars, respectively (Figure 6I). Finally, the INIAP 11 cultivar presented higher levels of Mg extraction (6.5 kg ha^{-1}), compared to INIAP 14 (6.2 kg ha^{-1}). Levels of Mg were higher in plants under FP3, with a mean extraction of 8.6 and 7.8 kg ha^{-1} for the INIAP 11 and INIAP 14 cultivars, respectively (Figure 6J).

Performance parameters

The number of panicles did not show significant differences due to the effects associated with the cultivar (p=1.00) and FPs (p=0.442) (Table 3).

Table 3: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions on panicle number (plant^{-1}).*

Cultivar	Fertilization program (FP)				
	FP1^{ns}	FP2^{ns}	FP3^{ns}	FP4^{ns}	FP5^{ns}
INIAP 11	28	29	30	28	29
INIAP 14	29	29	29	28	28
INIAP 11 control	30				
INIAP 14 control	27				

FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. ^{ns} non-significant differences according to the Scott-Knott's test (p>0.05). Values after ± represent the standard error of the mean.

The number of grains per panicle did not show significant differences due to either the effect of the cultivars (p=0.7714), or to the application of the FPs (p=0.2467). However, significant differences (p<0.001) were observed between the different treatment combinations (cultivar x FP) and the control treatments. Cultivars INIAP 11 and INIAP 14 showed mean grains $panicle^{-1}$ of 102 and 103, respectively, higher than the control treatments of both cultivars, whose mean was 81.6 grains $panicle^{-1}$ (Table 4).

Table 4: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions in the grain number (panicle^{-1}).*

Cultivar	Fertilization program (FP)				
	FP1^{ns}	FP2^{ns}	FP3^{ns}	FP4^{ns}	FP5^{ns}
INIAP 11	98 $^{*+}$	105^{*+}	106^{*+}	103^{*+}	99^{*+}
INIAP 14	101^{*+}	104^{*+}	1053^{*+}	101^{*+}	103^{*+}
INIAP 11 control	82				
INIAP 14 control	81				

*FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. ^{ns} non-significant differences according to the Scott-Knott´s test (p>0.05). Values followed by * and + differ from the INIAP 11 control and INIAP 14 control treatments according to the Dunnett´s test (p≤0.05). Values after ± represent the standard error of the mean.*

Grain weight $plant^{-1}$ was significantly affected by both the cultivar (p<0.001) and the FPs (p<0.001). In general, INIAP 11 presented a mean of 3.2 g, higher than INIAP 14 with 2.9 g. The mean weight of grains $plant^{-1}$ was higher under FP3, with mean weights of 3.96 (INIAP 11) and 3.52 g (INIAP 14). In relation to the control treatments, these presented the lowest values, with means of 2 (INIAP 11) and 1.9 g (INIAP 14) (Table 5).

Paddy rice yield was significantly affected by the cultivar (p<0.001) and FPs (p<0.001), as well as the interaction between both factors (p< 0.001). In general, the highest peel yield was exhibited by the INIAP 11 cultivar (7616.1 kg ha^{-1}), higher than INIAP 14 (7144.1 kg ha^{-1}). Both cultivars presented the highest yield under FP3, showing values of 9522.3 (INIAP 11) and 8463.3 kg ha^{-1} (INIAP 14) (Table 5). On the contrary, the lowest yields of paddy rice were presented by the control treatments with 4708.3 kg ha^{-1} (INIAP 11) and 4526.3 kg ha^{-1} (INIAP 14) (Table 6).

The final thrashed rice production was mainly affected by the FPs (p<0.001). Rice yield increased with nutrient inputs. The INIAP 11 cultivar had an increase in production from FP1 (2663.6 kg ha^{-1}), reaching a

Table 5: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions in grain weight (g).*

Cultivar	Fertilization program (FP)				
	FP1^ns^	**FP2**	**FP3**	**FP4**	**FP5^ns^**
INIAP 11	2.24 ± 0.04*+	3.03 ± 0.04a*+	3.96 ± 0.04a*+	3.53 ± 0.03a*+	3.08 ± 0.04*+
INIAP 14	2.27 ± 0.02*+	2.85 ± 0.04b*+	3.52 ± 0.03b*+	3.17 ± 0.06b*+	3.05 ± 0.04*+
INIAP 11 control	1.96 ± 0.04				
INIAP 14 control	1.89 ± 0.04				

*FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. ns non-significant differences. Different letters indicate significant differences by the Scott-Knott test ($p \leq 0.05$). Values followed by * and + differ from the INIAP 11 control and INIAP 14 control treatments according to the Dunnett test ($p \leq 0.05$). Values after ± represent the standard error of the mean.*

Table 6: *Effect of different fertilization programs (FP) on two rice cultivars (INIAP 11 and INIAP 14) under sodic soil conditions in husk rice yield (kg ha^{-1}).*

Cultivar	Fertilization program (FP)				
	FP1^ns^	**FP2**	**FP3**	**FP4**	**FP5^ns^**
INIAP 11	5400.00 ± 99.80*+	7271.66 ± 88.19a*+	9522.33 ± 95.15a*+	8484.33 ± 67.87a*+	7402.00 ± 84.35*+
INIAP 14	5457.00 ± 53.86*+	6857.00 ± 87.81b*+	8463.33 ± 64.50b*+	7613.66 ± 143.90b*+	7329.33 ± 100.72*+
INIAP 11 control	4708.33 ± 106.90				
INIAP 14 control	4526.33 ± 87.34				

*FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. ns non-significant differences. Different letters indicate significant differences by the Scott-Knott test ($p \leq 0.05$). Values followed by * and + differ from the INIAP 11 control and INIAP 14 control treatments according to the Dunnett test ($p \leq 0.05$). Values after ± represent the standard error of the mean.*

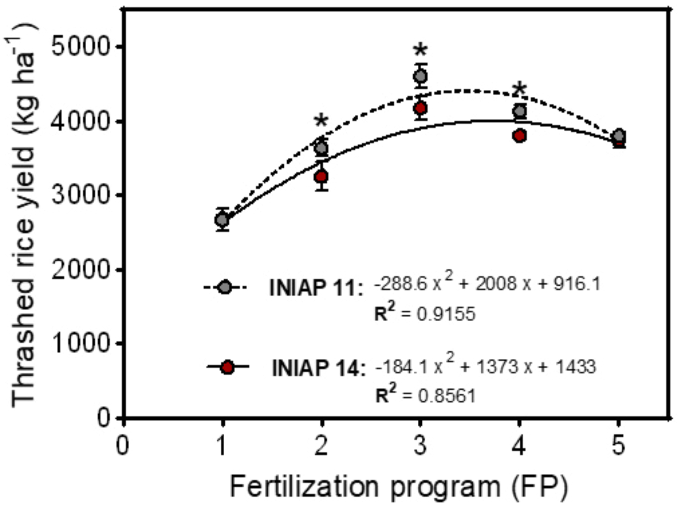

Figure 7: *Relation between increasing doses of fertilizers and thrashed rice yield (kg ha^{-1}) in two rice cultivars (INIAP 11 and INIAP 14). Fertilization programs based on N-P-K-Ca-Mg: FP1 = 35-3.3-6.3-40-15; FP2 = 70-6.6-12.5-80-30; FP3 = 105-9.8-18.8-120-45; FP4 = 140-13.1-25-160-60; FP5 = 175-16.4-31.3-200-75. Asterisks (*) indicate a statistically significant difference between both cultivars according to the t-Student test ($p \leq 0.05$). Error bars represent the standard error of the mean.*

production peak with the application of FP3 (4600.6 kg ha^{-1}) (Figure 7). Crop production began to decrease from FP4 and FP5 with mean yields of 4128.3 and 3798.3 kg ha^{-1}, respectively. Cultivar INAIP 14 presented a similar response to INIAP 11, production increasing from the application of FP1 (2673.3 kg ha^{-1}) and reaching a maximum under FP3 (4600.6 kg ha^{-1}). The yield in INIAP 14 began to decrease from FP4, showing a yield of 3736.6 kg ha^{-1} (Figure 7).

Nutrient agronomic efficiency (NAE) and nutrient recovery efficiency (NRE) showed an association with each other, and substantially influenced both growth and reproductive variables. The NAE of N, P, K, Ca and Mg, and the NRE of N, P, K, Ca and Mg were closely associated, covering 75% (component 1) of the total variation in the analysis of main components (Figure 8A). Grain weight panicle^{-1}, shell yield (kg ha^{-1}) and thrashed rice yield (kg ha^{-1}) showed a close relationship with each other, grouping predominantly in main component 2 (Figure 8B). On the other hand, the N AE, P AE, K AE, Ca AE and Mg AE together with N FRE, P FRE, K FRE, Ca FRE and Mg FRE had high quality of representation in the map factor (principal component 1), which is shown in Figure 8B. Finally, significant differences ($p \leq 0.05$) were observed between vegetative and reproductive

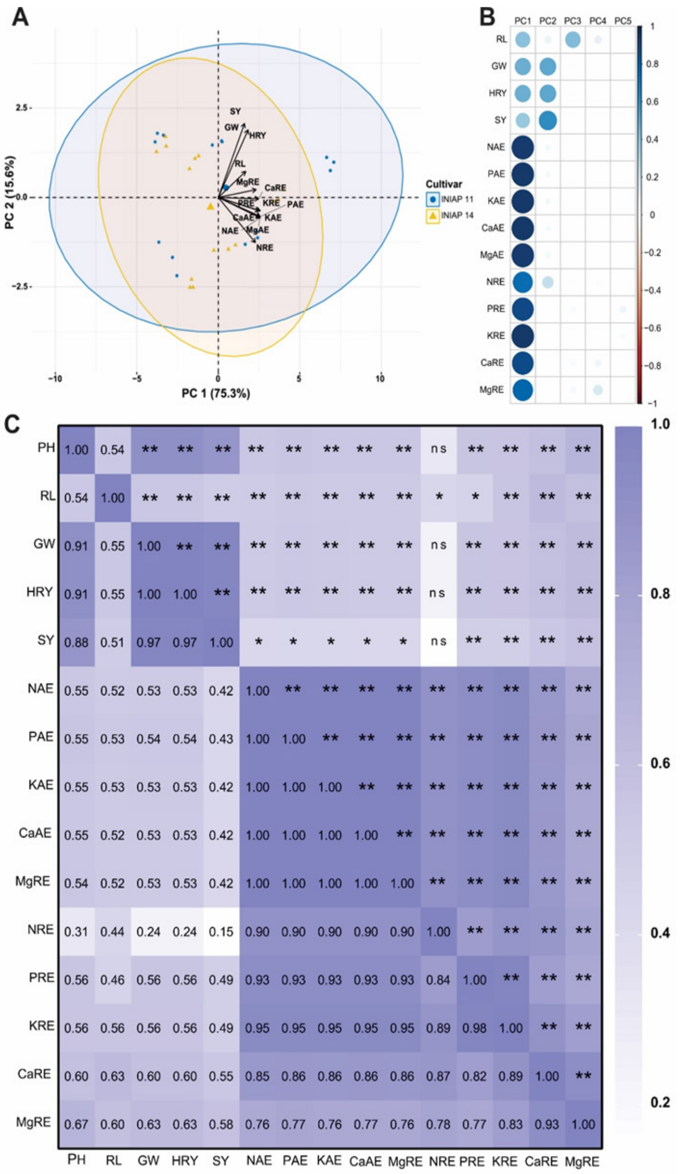

Figure 8: *Relationship between variables associated with increased crop yield in rice cultivation under sodic soil conditions. A) Principal component analysis (PCA). B) Quality of variable representation for each principal component. C) Pearson correlation (* p≤0.05; ** p<0.01) between vegetative and yield variables. PH = plant height; RL = root long; GW = weight grain; HRY = husk rice yield; SY = Staked yield; N AE = nitrogen agronomic efficiency; P AE = phosphorous agronomic efficiency; K AE = potassium agronomic efficiency; Ca AE = calcium agronomic efficiency; Mg AE = magnesium agronomic efficiency; N RE = nitrogen recovery efficiency; P RE = phosphorous recovery efficiency; K RE = potassium recovery efficiency; Ca RE = calcium recovery efficiency; Mg RE = magnesium recovery efficiency.*

growth variables. For example, the yield of thrashed rice showed high positive correlation with plant height and root length (p<0.001 and p=0.002). The AE of N, P, K, Ca and Mg showed high positive correlation with the yield of thrashed rice (p=0.02). In turn, the NRE of P, K, Ca and Mg showed a significant relationship with the yield of thrashed rice (p=0.004), except for the relationship between the NRE with the yield of piled rice, which presented no correlation (p=0.436).

The variables N AE, P AE, K AE, Ca AE and Mg AE showed a significant correlation with each other (p<0.001). Similarly, high correlation between them was observed in the variables N RE, P RE, K RE, Ca RE and Mg RE (p<0.001) (Figure 8C).

The research results showed that growth parameters such as plant height, root length and plant dry weight were influenced by the fertilization programs and planting cultivar. Plants treated with FP3 presented higher means in plant height of both rice cultivars (INIAP 11 and INIAP 14). As in most cereals, N is essential for plant growth, constituting the structural part of proteins and chlorophyll, stimulating vegetative growth (Pramanik and Bera, 2013). Studies show that the growth in height of rice plants (90 days after transplanting) was greater as the supply of N levels increased (Shankar *et al*., 2020). On the contrary, the lowest growth response was manifested with the FP1 and FP5 treatments. The above indicates that the poor supply of nutrients and excess of fertilizers can cause deficiency and toxicity problems in plants, respectively (Good and Beatty, 2011). Similarly, Yadav *et al*. (2017) indicate that a N deficiency in rice plants causes slow growth and leaf yellowing due to lack of chlorophyll, compromising the general health of the crop. For China, it was suggested that reducing fertilizer application from 60 to 30% for wheat, corn and rice could be implemented while maintaining current crop yields (Ju *et al*., 2009).

In the present study the accumulation of dry biomass was higher in FP3 in relation to the rest of the fertilization programs. Research reveals that nutrient management practices exerted a positive and significant effect on dry matter accumulation. For example, the maximum accumulation of dry matter was recorded in plants that received a contribution of 75% of fertilizers, and these plants differed from those that were not fertilized, which presented reduced accumulation of dry matter (Shankar *et al*., 2020). The improvement in rice biomass when applying the aforementioned amount of nutrients may be due to an optimal balance between the amount of nutrients supplied and the real needs of the plant, which can maximize the efficiency of nutrient absorption and promote healthy growth without excess or deficiency of nutrients, as stated by Haider *et al*. (2023). This clearly indicates the need for a balanced contribution of fertilizers to promote crop growth in terms of dry matter accumulation, which will translate into greater productivity (Shankar *et al*., 2020). The analysis of the chemical properties of the soil is essential prior to establishing a fertilization program, constituting a key measure in determining the appropriate and balanced amounts of nutrients (Hartz, 2003). Shankar *et al*. (2021) mentioned that growth parameters, such as biomass production, leaf area index and number of tillers improved in treatments with adequate nutrient management. Similarly, Ullah *et al*. (2019) point out that adequate nutrient management with the selection of an adapted cultivar promoted greater growth of roots, tillers, and accumulation of plant biomass.

The concentration of nutrients in the grain (GNC) was higher with FP3 and the INIAP 11 cultivar. A series of factors can affect the CNG, which will have a close relationship with the final yield of the crop (Thakur *et al*., 2020). This parameter allows evaluating the removal of nutrients by the crop, the efficiency of nutrient use, determining future nutrient needs and guidelines for the development of fertilizer recommendations (Rakotoson *et al*., 2023). Du *et al*. (2013) mention that CNG is information of interest to know the quality of a product for human consumption. Access to this information can contribute to generating satisfactory mean yields, with nutritionally superior quality, while reducing the environmental footprint (Rakotoson *et al*., 2023).

Studies on cereals in various regions of the world suggest that environmental factors such as climatic conditions (Du *et al*., 2013; Shimoyanagi *et al*., 2021), nutrient supply, management practices, including fertilizer applications (Haefele *et al*., 2022; Ludemann *et al*., 2022) and crop genotype (Johnson *et al*., 2021) are the factors that have the greatest impact on variations in nutrient concentration in the grain (Huang *et al*., 2016; Pinson *et al*., 2015). For example, macronutrient concentrations in grains of numerous cultivars of cultivated rice 529 (Chen *et al*., 2014) showed phenotypic variations that were from 10 % to 38 % N, P, K, Ca and Mg (Yang *et al*., 2018). It has also been noted that extensive nutrient remobilization during the reproductive stage depends on the specific nutrient requirement, nutrient uptake rate, and nutrient availability in the soil (Rakotoson *et al*., 2023).

The results of this research indicate that the greatest agronomic efficiency (AE) of N, P, K, Ca and Mg was achieved through the application of FP3, while, at the cultivar level, the AE of INIAP 11 was higher than in INIAP 14. Crop yields improve when fertilizers are applied in the appropriate place, source, quantity and stage of development, increasing the efficiency of the nutrients applied (Shankar *et al*., 2021). In this way, the correct supply of N will improve the formation of organs, physiological and performance parameters (Maathuis, 2009). The correct supply of P guarantees the supply of energy for multiple metabolic processes and, in the case of K, it contributes to cellular osmotic control, enzyme activation and protein transfer through membranes (Maathuis, 2009).

The EAN was always lower with the application of the highest dose of nutrients (FP5). The excessive addition of fertilizers is not always a guarantee of greater nutrient efficiency (Good and Beatty, 2011). The above is in accordance with the results of the present investigation, where the excessive application of fertilizers reduced the efficiency of nutrient use. During the last two decades, nutrient management has gained importance to maximize their effective use (Baligar *et al*., 2001). Nutrient AE is usually expressed as the fertilizer capacity recovered by the aboveground biomass throughout the crop season (Shankar *et al*., 2021). For example, it was observed that N use efficiency showed a relationship between dry matter production or economic performance and the amount of N applied (Zhang *et al*., 2023). It has been estimated that N use efficiency ranges from 30 to 50 % for cereal crops, while P use efficiency is even lower than 30 % (Raun and Johnson, 1999; López-Arredondo *et al*., 2014).

Nutrient recovery efficiency (NRE) can be significantly affected by the cultivar sown (Fageria *et al*., 2008). The results show that the nutrient recovery rate was higher in INIAP 11. The adoption of key agronomic practices for improving the efficient use and recovery of nutrients includes the selection of a variety that has greater nutrient recovery capacity (Zhang *et al*., 2023). For this reason, the efficient use of nutrients can be seen from the point of view of crop yield and nutrient removal (Shankar *et al*., 2021). On the other hand, it was observed that nutrient management practices exerted a significant impact on the efficient use of nutrients for grain, physiological efficiency, and apparent nutrient recovery efficiency (Sai-Ram *et al*., 2020).

In our trials, rice plants showed increasing levels of extraction of all elements from FP1 to FP3. On the contrary, lower levels of nutrient extraction were presented by FP1. In contrast, after the application of FP4 and FP5, nutrient extraction levels began to gradually decrease. Studies indicate that the highest extraction levels of N (119.71 kg ha^{-1}), P (32.81 kg ha^{-1}) and K (14.48 kg ha^{-1}) in rice grains were obtained with the 80-20-. 20, 80-40-10 and 80-20-60 fertilization programs respectively (Sahu *et al*., 2017). The extraction of N (85.6 kg/ha^{-1}), P (28.1 kg/ha^{-1}) and K (128.7 kg/ha^{-1}) in rice was greater with the contribution of 255.0 kg ha^{-1} of N, 16.7 kg ha^{-1} of P and 144.0 kg ha^{-1} of K, respectively (Sai-Ram *et al*., 2020). Currently, high-yielding cultivars are highly demanding in nutritional requirements, resulting in the substantial removal of nutrients, with a direct effect on crop yield (Pawar *et al*., 2017). This situation has led to the excessive use of synthetic fertilizers without a balanced contribution of essential nutrients for the growth and development of plants (Hossain and Singh, 2000).

Yield parameters such as grain weight, husk yield and threshed rice yield improved substantially with the implementation of FP3. Fertilization programs lower or higher than FP3 did not show satisfactory yields. Integrated nutrient management practices exerted an evident effect on growth parameters such as the number of panicles, number of grains per panicle and grain weight (Sai-Ram *et al*., 2020; Shankar *et al*., 2021). It is suggested that the balance between crop yield, quality and soil nutrient status can be manipulated by exploiting nutritional interactions and appropriate fertilizer application (Li *et al*., 2019). Furthermore, the implementation of agronomic practices based on the genetic approach, that is, the use of a feasible and adapted cultivar, can increase food production by 15 to 20% (Peng *et al*., 2010). Hence, sustainable production of rice cultivation is achieved with global standards of quantity and quality by maintaining fertility, the result of integrated nutrient management (Sahu *et al*., 2017; Ullah *et al*., 2019; Shankar *et al*., 2020; Shrestha *et al*., 2020). Frequently, many production systems only focus on the efficient use of N, neglecting the contribution of other macronutrients (Goulding *et al*., 2008). The availability of N, P and K in the soil after harvest were significantly affected; therefore, the balanced contribution of these elements in each planting season is essential to conserve soil nutrient reserves (Sai-Ram *et al*., 2020).

Conclusions and Recommendations

The type of genetic material and fertilization programs (FP) had a significant impact on the vegetative growth parameters and productive performance of the rice crop. The FP3 stands out for promoting a higher yield of thrashed rice, in both the INIAP 11 and INIAP 14 cultivars. These findings highlight the importance of appropriately selecting a fertilization program optimizing the use of nutrients and enhance threshed grain yield in the sustainable production of the rice cultivation under sodic soil conditions.

The maximum rice production in the INIAP 11 cultivar is obtained by applying 3.4 portion to obtain grain yields of 9031 kg ha^{-1}, whereas in the INIAP 14 cultivar, it is required to apply 3.54 proportions of FP to obtain 8098 kg ha^{-1}.

The production and scientific publication of technical results, such as ours, constitute a resource with pertinent technical information, easy to apply and/or adapt to rice production systems of small and medium-sized farmers affected by sodic soil conditions. Therefore, it is recommended to increase technical publications of this type, so that they contribute to the improvement of rice crop productivity levels, improving resource management and the economy of producers.

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Novelty Statement

This study highlights how balanced fertilization optimizes nutrient efficiency in rice grown under sodic soil conditions, providing an innovative strategy to improve crop yields in high-salinity environments.

Author's Contribution

Carlos Loor: Conceptualization, research, methodology, writing, original draft, writing review and editing, obtaining funding, project administration. **Edisson Cuenca:** Conceptualization, research, methodology, writing, original draft, writing review and editing, visualization.

Francisco Arteaga: Conceptualization, research, methodology, validation, writing, review and editing.
Luis Saltos: Formal analysis, research, supervision, visualization, writing original draft, writing review and editing.

Conflict of interest

The authors declare that there is no conflict of interest among the authors of the manuscript. All authors have independently participated in the development of this research and have not received external influences that could affect the content or results presented in the manuscript.

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