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Constraints in Irrigated Lowland Rice Cultivation as Affected by the Harmattan in Guinean Savanna Zone of 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

Lowland rice accounts for about 36% of the total rice area in Côte d'Ivoire and contributes over 20% of total paddy production. Lowland rice cultivation under flooded or irrigated conditions has a potential average yield of 6-8 t/ha, with the possibility of two cropping cycles per year. Despite the availability of water in these lowlands, which could allow three cropping cycles per year, farmers are limited to two cycles due to the impact of the Harmattan, which occurs in the last trimester of the year and severely affects yields. Harmattan is characterised by low temperatures associated with dusty winds during two-thirds of the dry season in the bimodal rainfall area of the Guinea savannah in West Africa. This particular climate adversely affects rice production even in irrigable lowland perimeters, allowing only one cycle of rice production instead of two or three. In order to improve rice production in this agroclimate, it is necessary to diagnose the constraints. Two agronomic trials were conducted in the irrigable valley of M'bé II, in a Guinea savannah zone of central Côte d'Ivoire. The first trial was an omission trial (Fc-N, Fc-P, Fc-K, Fc-Ca, Fc-Mg and Fc-Zn) with a complete fertiliser (Fc) consisting of 30 kg N ha^{-1}, 60 kg P ha^{-1}, 50 kg K ha^{-1}, 50 kg Ca ha^{-1}, 50 kg Mg ha^{-1} and 10 kg Zn ha^{-1}. The control was no fertiliser treatment. All treatments consisted of NPK applied at the same rates and Ca (0, 50, 100 and 150 kg ha^{-1}), Mg (0, 50, 100 and 150 kg ha^{-1}) and Zn (0, 10, 20 and 30 kg ha^{-1}) added in the respective treatments. The application of N, K and Mg can increase the yield of irrigated rice in the Harmattan period. Further improvement can be observed by combining 90 kg Ca ha^{-1} with NPK.

Keywords: Calcium; harmattan; magnesium; nitrogen; rice production.

1. INTRODUCTION

Lowland irrigated rice (*Oryza sativa* L.) is considered one of the most promising cropping systems in sub-Saharan Africa because of its high yield potential, which can reach 6 to 8 tonnes per hectare per cropping cycle, with the possibility of two to three harvests per year under favourable conditions. However, in the Guinea savanna zone of West Africa, the sustainability of this system is increasingly challenged by agroclimatic constraints, notably the seasonal occurrence of the harmattan. This dry and dusty wind, which dominates about two-thirds of the dry season (Ferguson, 1985), is associated with low ambient temperatures, high evapotranspiration and reduced atmospheric humidity - factors known to affect plant physiological processes. Despite the availability of improved rice varieties and the development of irrigation infrastructure, grain yields remain alarmingly low, often falling below 1 t-ha^{-1} in irrigable lowland perimeters during the dry season. This paradox raises concerns about underlying production constraints beyond genetics and water availability. The main issue addressed in this study is the poor understanding of mineral nutrient dynamics under harmattan induced stress. In particular, it is hypothesised that nutrient depletion, especially of exchangeable base cations such as calcium (Ca), magnesium (Mg) and zinc (Zn), may significantly affect the physiological functioning and yield potential of rice during this critical period. These nutrients are known to play a pivotal role in photosynthesis, membrane stability and nutrient uptake, and their deficiencies could be exacerbated by the harsh environmental conditions imposed by harmattan. Therefore, the general objective of this study was to improve the productivity of irrigated lowland rice during the dry season under harmattan conditions through optimised nutrient management. Specifically, the study aimed to Identify the limiting nutrients in rice production under harmattan stress through omission experiments;

1. Assess the contribution of exchangeable cations (Ca, Mg and Zn) when applied in combination with macronutrients (N, P and K);
2. Determine the most effective nutrient combination to improve physiological functions and maximise grain yield of rice during the harmattan season.

To achieve these objectives, two field experiments were conducted during the 2011 dry season: an omission trial to diagnose soil nutrient deficiencies and a factorial trial to assess rice response to exchangeable cations in combination with NPK fertiliser. These studies are expected to provide agronomic knowledge for the development of nutrient management strategies adapted to the climatic constraints of the harmattan period.

2. MATERIALS AND METHODS

2.1 Site Description

The experiments were carried out in the valley of M'Bé II (8º06N, 6º00W, 180 m) in central Côte d'Ivoire, a Guinean savannah zone with a bimodal rainfall pattern. The soil was a fluvisol of secondary hydrographic network. The site was irrigable throughout the year, and the experimental plot was a ten-year-old fallow field composed mainly of Leersia hexandra (Poaceaes).

2.2 Experiment Layout

The omission experiment consisted of a complete fertiliser Fc (30 kg N ha-1-[CO(NH 2)2, 46% N]; 60 kg P ha^{-1} [Ca(H2PO4)2-H2O, 18-22% P]; 50 kg K ha-1-[KCl; 50% K]; 50 kg Ca ha^{-1} [CaCO3; 40% Ca]; 50 kg Mg ha^{-1} [MgSO4.H2O, 17% Mg] and 10 kg Zn ha^{-1} [ZnSO4H2O, 36% Zn]) from which one specific nutrient was excluded for each treatment (Fc-N, Fc-P, Fc-K, Fc-Ca, Fc-Mg and Fc-Zn). No fertiliser treatment (F0) was the control. The same types and rates of NPK were combined with 50 kg Ca and Mg ha^{-1} (Ca^{2+} and Mg^{2+}), 100 kg Ca and Mg ha^{-1} (Ca^{2+} and Mg^{2+}) and 150 kg ha^{-1} Ca and Mg (Ca^{2+} and Mg^{2+}). Furthermore, 10 kg Zn ha^{-1} (Zn^{2+}), 20 kg Zn ha^{-1} (Zn^{2+}) and 30 kg Zn ha^{-1} (Zn^{2+}) were combined with NPK. The fertilisers were applied as basal before transplanting (20 cm × 20 cm) the rice variety NERICA L19 in a randomised complete block design. The plots (5 m × 3 m) were irrigated once a month and hand weeded twice at the tillering and top dressing stages of the rice before applying additional N fertiliser at 25 kg ha^{-1} each time.

2.3 Data Collection and Processing

Before the start of the experiment, soil samples were taken from the four corners and the centre of the site at a depth of 0-20 cm using a hand auger. A composite soil sample was taken for laboratory analysis: the electrode method was used for pH-water (1:1.25) and the oxidation method for organic C. Nitrogen and available P contents were determined by the Kjeldahl and Olsen methods respectively, while the acetate ammonium method was used for exchangeable cation extraction, before atomic absorption spectrometry was used to measure Ca, Mg and EC in the soil. Flame spectrometry was used for soil K content. The occurrence of submergence was recorded as zero-0 and one-1 for its absence and occurrence, respectively. When the rice was mature, the number of plants and tillers per square metre was counted in the absence trial. Each treatment in both trials was harvested in 8 m2, leaving two border lines. Rice grain yield was calculated at a standard moisture content of 14%. Grain and straw samples were analysed for nitrogen concentration.

2.4 Statistical Analysis

Pearson correlation analysis was carried out to show the relationship between the occurrence of submergence, tillering damage, plant death rate and rice grain yield recorded in the omission trial. Analysis of variance was done for grain yield and plant tissue nutrient concentration according to treatments in each trial. Response curve analysis was used to determine the optimum dose of Ca as the most important cation in rice nutrition during the second trial. The means were separated by least significant difference for α = 0.05 using the SAS package. 10.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Soil chemical content of the study area in 0 – 20 cm depth

Table 1 Soil chemical characteristics in 0 – 20 cm depth

Parameters	Values
pHwater	5.5
Organic-C (gkg^{-1})	3.12
Total-N (gkg^{-1})	0.31
Available-P ($mgkg^{-1}$)-Olsen	150
K ($cmolkg^{-1}$)	0.08
Ca ($cmolkg^{-1}$)	3.05
Mg ($cmolkg^{-1}$)	2.26
CEC ($cmolkg^{-1}$)	20.2

Nitrogen (N), potassium (K) and soil organic carbon concentrations are below their respective critical levels, indicating potential deficiencies that could affect crop productivity. The soil pH indicates an acidic reaction, which may affect the availability of certain nutrients. On the other hand, magnesium (Mg), calcium, assimilable phosphorus and CEC are relatively high, which may indicate a potential saturation of these elements in the soil, with implications for fertility management and nutrient competition.

3.1.2 Grain yield obtained according to the treatments

Grain yield decreased significantly from treatment Fc-Zn to control F0.

The lowest grain yields were recorded for the Fc-N, Fc-K and Fc-Mg treatments, which were not significantly different from the control treatment. On the other hand, the highest yield was observed for the FC-Zn treatment, followed by the FC-Ca, FC, FC-P and FC-S treatments, which were statistically equivalent.

3.1.3 Study of factors affecting rice grain yield and nitrogen concentration in rice grain and straw according to the treatments

Significant and negative correlation is observed between the occurrence of submersion and the rice grain yield as well as between this parameter and the dead ratio of rice plant.

Table 2 shows the correlations between grain yield and the constraints encountered during the experiment. A significant negative correlation was observed between grain yield and mortality and intermittent flooding of the plots. In addition, a positive correlation was found between flooding and the mortality of the rice plants.

The highest nitrogen uptake ratio was observed in the rice straw in the Fc-Mg treatment. The highest uptake ratios in the grain were recorded in the FC-Ca and FC treatments. In contrast, the ratios in the other treatments were relatively low compared to those mentioned above. However, these treatments had the highest concentrations in the straw.

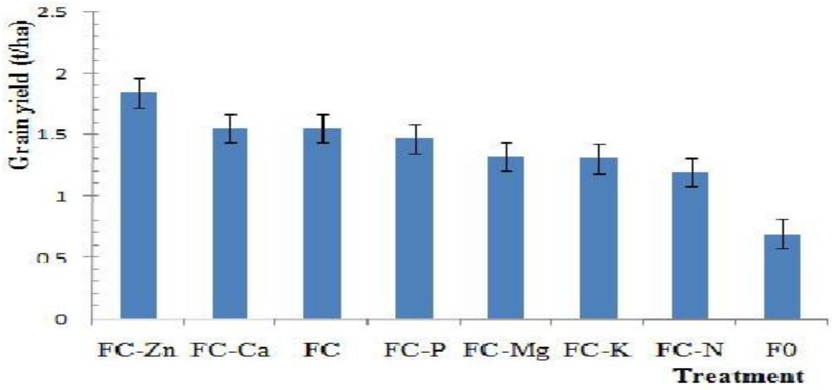

Fig. 1. Rice grain yield mean value per treatment in omission trial

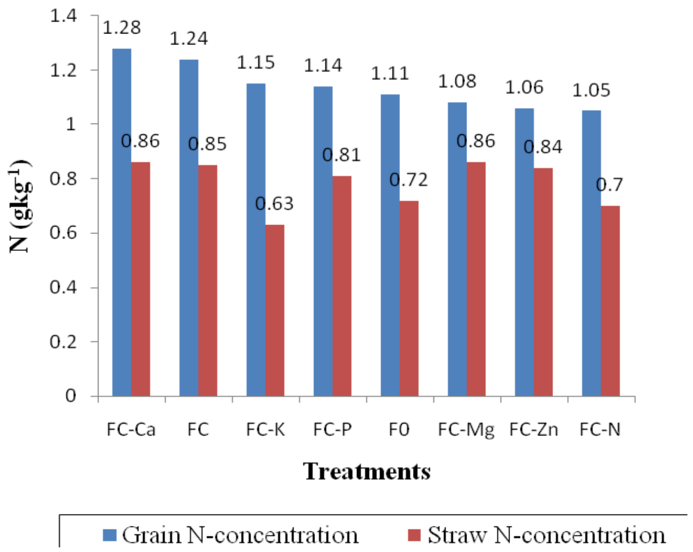

Fig. 2. Nitrogen concentration in rice grain and straw according to the treatments

Table 2. Pearson correlation coefficient and probability

Parameters	Coefficients of correlation-R	Probability
Dead ratio × Grain yield	-0.546	0.0012
Submersion × Grain yield	-0.382	0.031
Grain yield × Tiller damages	-0.018	0.921
Submersion × Tiller damages	0.363	0.041

3.1.4 Rice grain yield according to treatments in the second trial

Fig. 3 shows a significantly higher grain yield for the NPK treatment supplemented with 100 kg Ca ha-1 ($NPKCa^{2+}$), which had the highest agronomic performance. This was followed by the NPKMg2 treatment. In contrast, the NPKMg3 treatment had the lowest grain yield of all the treatments evaluated.

The optimum rate of Ca was determined at 90 kg ha^{-1}. At the particular rate of Ca, we also observe the optimum concentration of N- in the grain.

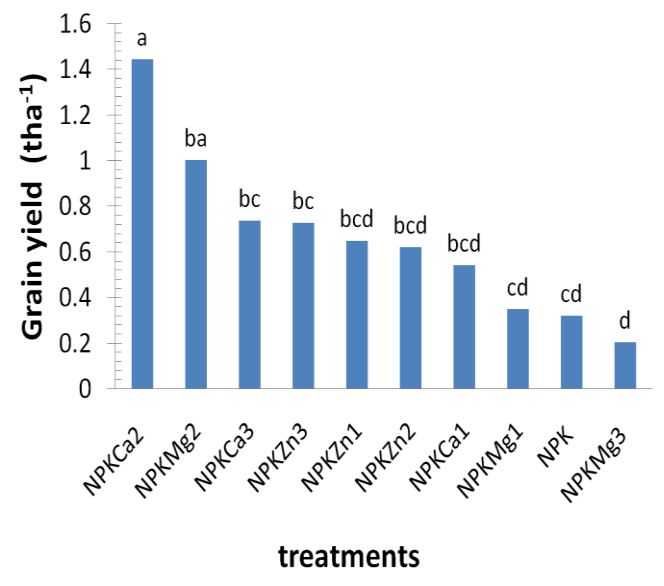

Fig. 3. Rice grain yield according to treatments in the second trial

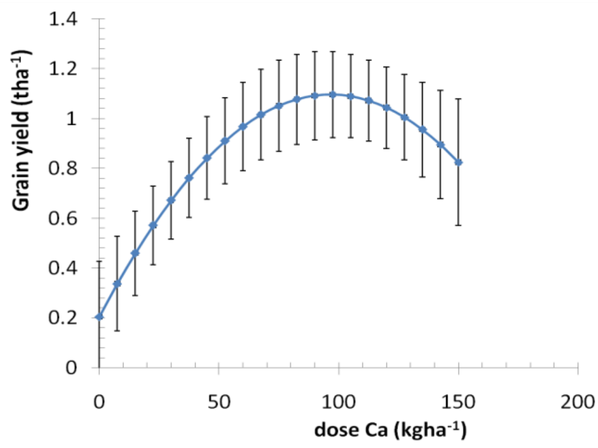

Fig. 4. Rice response curve to Calcium rates

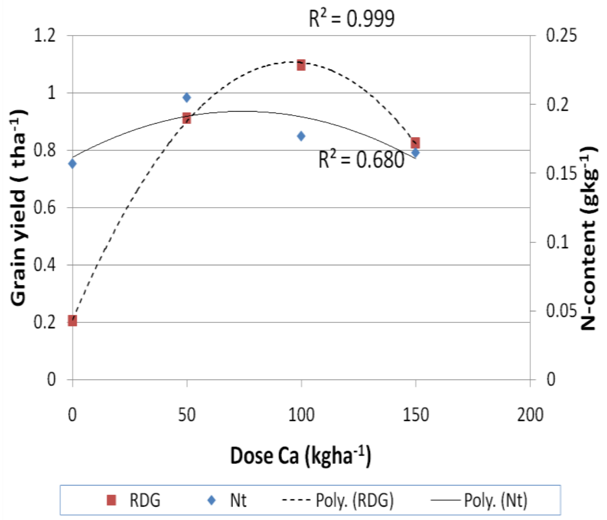

Fig. 5. The regression of grain yield and N-concentration in the grain

3.2 Discussion

The notably low grain yields recorded in treatments Fc-N and Fc-K can be attributed to the intrinsic deficiency of nitrogen (N) and potassium (K) in the soil, both falling below their critical thresholds. However, the reduced yield observed in Fc-Mg is paradoxical, given the high baseline magnesium (Mg) levels in the soil. Interestingly, the elevated N-uptake in the straw in the Fc-Mg treatment suggests impaired nitrogen translocation to the grain, likely due to a disruption in the synergistic interaction between N and Mg during rice nutrition (Ding et al., 2006). Although soil Mg levels were sufficient, its bioavailability and uptake into rice grains remained suboptimal. This inefficiency can be attributed to physiological constraints potentially exacerbated by the harsh climatic conditions induced by the Harmattan season, which is characterized by low atmospheric humidity, increased evapotranspiration, and reduced cloud cover all factors that impede nutrient uptake (Oteyami et al., 2019). Magnesium is indispensable for photosynthesis, chlorophyll biosynthesis, and the enhancement of nitrogen-use efficiency in rice (Ali et al., 2021). Under abiotic stress, such as that caused by the Harmattan, foliar applications of Mg at key phenological stages have shown positive effects on rice yield under both aerobic and irrigated systems (Gabasawa, 2021). Furthermore, Mg deficiency has been associated with the accumulation of reactive oxygen species and a cascade of enzymatic dysfunctions, culminating in reduced nitrogen-use efficiency, compromised root development, and impaired grain filling (Kirk et al., 2022). This finding underscores the essential synergism between N and Mg in rice mineral nutrition (Lin et al., 2014; Urmi et al., 2022). When one element is physiologically limited, the function of the other is likewise impaired. This disruption may also be amplified by potassium induced antagonism, which hinders Mg uptake (Epstein, 1972). While secondary in effect, such antagonism can reduce Mg's role in carbohydrate synthesis and assimilate transport, further limiting grain filling (Mengel & Kirkby, 1982). In addition to nutrient related issues, poor land management led to transient field submersion and plant mortality, further reducing yield. Climatic data recorded during the experiment showed temperature variations between 20–21 °C (min) and 33–34 °C (max). Although suitable for grain filling (20–25 °C), the cooler temperatures during the vegetative phase fell below the optimal tillering range (25–31 °C) (Berhe, 2013). Low temperatures degrade chloroplasts and trigger the mislocalization of plastidic enzymatic processes to the cytoplasm, ultimately disrupting plant development (Lin et al., 2014, Konan., 2013). Consequences include delayed emergence, weak vegetative growth, foliar discoloration, delayed flowering, spikelet sterility, and incomplete panicle development. The Harmattan, a dry and dusty wind originating from the Sahara, profoundly alters agro-climatic parameters in West Africa. Its multifaceted impacts on crop physiology particularly through hydric and oxidative stress necessitate strategic interventions (Oteyami et al., 2019; Ekele, 2022). These may include improved varieties, foliar nutrient applications, and water management systems adapted to stress conditions. Moreover, no significant response to calcium at 50 kg ha^{-1} was observed in the omission trial. However, in a follow-up trial, the application of 100 kg Ca ha^{-1} substantially improved grain yield. This response is likely an indirect effect mediated through enhanced nitrogen assimilation, as calcium is known to synergize with N in plant nutrition (Saijo et al., 2001; Diatta & Koné, 2001). Calcium also facilitates enzymatic function and nitrate transport crucial for mitochondrial development and cellular respiration (Lamrani, 2010). Our data indicate that an optimal synergistic effect is achieved at 90 kg Ca ha^{-1}, especially under Harmattan-induced stress conditions. These findings highlight the critical role of stable climatic conditions in rice cultivation and underscore the importance of adopting adaptive agronomic strategies. These include the use of stress-tolerant varieties, precise water management, and cultivation practices aimed at mitigating the adverse effects of the Harmattan (Ekele, 2022).

4. CONCLUSION

The manifestation of Harmattan induced stress was primarily reflected through the deleterious effects of low temperatures on the reproductive structures and physiological functions of rice plants. In addition to thermal constraints, the study underscored the importance of factors often overlooked in irrigable lowland ecosystems, such as transient submergence and inadequate water satisfaction, which now emerge as significant limiting factors. These were further compounded by mineral deficiencies, particularly under Harmattan conditions. The experimental findings clearly established nitrogen (N) and potassium (K) as essential macronutrients for optimal grain yield in irrigated rice cultivation. Moreover, a notable antagonistic interaction was observed between magnesium (Mg) and nitrogen uptake, indicating that Mg plays a modulating role in N efficiency. This interaction highlights the necessity of including Mg in the formulation of base fertilizers. The results also suggest that integrating calcium (Ca) and Mg with N and K significantly enhances yield performance. Nonetheless, the beneficial effects of fertilization may be offset by inadequate land management practices, particularly those leading to excessive waterlogging or poor drainage. Consequently, a balanced fertilization strategy involving the application of 80 kg N ha^{-1}, 50 kg K ha^{-1}, 90 kg Ca ha^{-1}, and 50 kg Mg ha^{-1} is recommended to mitigate the adverse impacts of Harmattan in irrigated rice systems. However, this must be accompanied by improved land and water management to ensure optimal nutrient use efficiency and sustainable yield outcomes.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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