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Linking Soil Fertility and Production Constraints with Local Knowledge and Practices for Two Different Mangrove Swamp Rice Agroecologies, Guinea-Bissau, West Africa

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Abstract: Mangrove swamp rice (MSR) production is critical for the diet of small farmers of coastal Guinea-Bissau. In mangrove swamp agroecosystems, rice is grown during the rainy season when freshwater and nutrients are abundant. However, small-scale farmers face challenges like unpredictable rainfall and rising sea levels, which increase soil salinity and acidity. This study aims to assess soil physical–chemical properties, paired with farmers' local practices, to evaluate fertility constraints, and to support sustainable soil–plant management practices. This co-designed research contributes to filling a gap concerning the adoption of sustainable agricultural practices adapted to specific contexts in West Africa. In two regions, Oio (center) and Tombali (south), rice yields were measured in semi-controlled trials both in two agroecological settings: Tidal Mangrove (TM) and Associated Mangrove (AM) fields. 380 soil samples were collected, and rice growing parameters were assessed during the 2021 and 2022 rice sowing, transplanting, and flowering periods. Principal Component Analyses (PCA) and Multivariate Regression Analysis (MRA) were applied to understand trends and build fertility proxies in predicting yields. Significant spatial and temporal variability in the soil properties between agroecologies was found. Salinity constraints in Oio TMs limit production to an average of 110 g/m^2, compared to 250 g/m^2 in Tombali. Yield predictions account for 81% and 56.9% of the variance in TMs and AMs, respectively. Variables such as organic matter (OM), nitrogen (N), potassium (K), and precipitation positively influence yields, whereas sand content, pH, and iron oxides show a negative effect. This study advances the understanding of MSR production in Guinea-Bissau and underscores the importance of incorporating farmers' knowledge of their diverse and complex production systems to effectively address these challenges.

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1. Introduction

Rice (*Oryza* spp.) cultivation is vital in most West African countries. It provides a livelihood for millions of people to whom this cereal is a staple food, deeply embedded in culinary and cultural practices, and crucial for food security [1]. At present, the achievement of rice self-sufficiency has become a challenge for Guinea-Bissau coastal smallholders producing in modified former mangrove soils. Although mangrove swamp rice (MSR) agroecologies are more fertile than inland swamps and uplands, this rice production system is experiencing increased vulnerability due to environmental constraints associated with climate change (irregular start, end, distribution patterns of rainfalls, floods, sea-level rise, and extreme tides, increase in pests and diseases attacks) and socio-economic transformations (e.g., rural exodus and market instability). These adverse conditions contribute to the occurrence of a hungry season prior to the next harvests, forcing farmers to borrow at high interest rates or to buy at high prices imported rice. Indeed, although rice imports have been undergoing yearly fluctuations [2], they rated in first place with 22% of imports in 2016 [3].

Focused on the low-lying fields of mangrove agroecology, Baggie et al. [4] categorized them depending on the salt-free period. However, throughout the extended periods of field observation, it became evident that the Tidal Mangrove (TM) and Associated Mangrove (AM) nomenclature proposed by Van Gent and Ukkerman [5] most accurately represents and identifies the MSR conditions. These authors detailed the unique mangrove swamp rice farming system in Guinea-Bissau, categorizing the fields into two main types (high-lying and low-lying) and six sub-categories based on their specific soil and water conditions. The high-lying fields, the AM agroecology, are free from salt intrusion and are significantly influenced by surface runoff. In contrast, the low-lying fields, referred to as TM agroecology, are notably affected by salt from tidal and river discharge. The AM fields were then divided into (a) fields with favorable soil properties; (b) fields neighboring the terrace; (c) fields with salinity problems; and (d) fields with limited drainage. The low-lying TM fields were then divided into (a) fields with sufficient drainage and (b) fields with limited drainage.

In the MSR production system, the cereal is cultivated in polders created after the construction of a main dike in former mangrove forests, where the soils were temporarily or permanently flooded by brackish water. Extensive areas of sulphidic clay soils are reported in West Africa and especially in the Niger Delta, the Gambia, and Guinea coastal rip [6]. Acid sulfate soils (ASS) occur naturally in coastal settings where waterlogged conditions with organic matter, iron, and sulfate are or have been present. When ASS undergoes oxidation excavated or drained the reduced iron sulfide minerals such as Pyrite, sulfuric acids are released, bringing soil pH below 4. This phenomenon can often be exhibited by yellow, orange, and red mottling in the soil profile, as an expression of the presence of intermediate products of sulfide oxidation such as jarosite, goethite, and hematite, which can accumulate even in the upper soil horizons [7,8].

These soil characteristics have a direct impact on rice growing. Acidity and high iron concentrations in these soils release reduced iron (Fe^{2+}) and oxidize water in the rice fields, which inhibits the physiological processes of the plant, leading to significant yield losses [9]. Pyrite (FeS_2) formations are common in this environment sometimes eroding the sulphidic materials in the tidal zones and forming the so-called "tannes" (barren highly saline flats) [6], frequently found in the coastal zones of Guinea Bissau, abandoned by farmers. Additionally, the high clay content in the paddy soils drastically limits the primary nutrient concentrations and mineralization [10].

In natural unfertilized rice paddy soils, nitrogen incorporation occurs solely from the fresh organic matter and weed decomposition which in turn contribute to the crop yields [11]. This is mostly the case of AM agroecologies, because in TM agroecologies the contributions of incoming suspended matter by the brackish water entrance are considerably important [12]. Further, evidence indicates that soil organic matter better accumulates in the topsoil of paddy soils in comparison to upland rice soils under the same climate conditions [13]. Van Keulen [14] demonstrated that the efficiency with which plants use N to produce grains varies with environmental conditions and the rice variety. However, as reported in the physicochemical characterization study in Merkohasanaj et al. [15], the MSR soils present important spatial differences among the studied regions and within agroecologies of the same region. Rice production in these agroecologies is primarily governed by rainwater accumulation. The "available water" defined as the depth of water (in cm) covering the ridges is a critical factor in ensuring that the crop's water needs are met throughout the growing season.

The above-mentioned problems, soil salinization, and acidification of many areas have led to a significant decline in production and resulted in the abandonment of many plots and changes related to the choice of varieties, cultivation and practices, and diversification into agricultural and non-agricultural activities. Varieties from both *Oryza glaberrima* and *O. sativa* are cultivated in MSR in Guinea-Bissau (e.g., [16,17]). While research confirms that *O. sativa* yields are usually higher, *O. glaberrima* varieties show higher resistance to various stresses [18–20], such as superior weed competitiveness [21,22], salinity tolerance [23,24], or drought [25]. Although *O. glaberrima* has been cultivated in rainfed ecosystems without any fertilizers, there have been very few studies demonstrating its adaptation to lowland rainfed Acid Sulfate Soils (ASS) (see Okry et al. [26] and Nuijten et al. [27] for upland and freshwater swamp agroecologies).

Farmers increasingly abandon unfertile, problematic fields and try to open new plots in search of more productive areas in the surrounding mangrove forests. Although mangrove forests have been increasing at a country level, and in 2015 occupied 47% more of the territory than in 1990 [28], national and international concerns about blue carbon decrease and the role of mangroves as carbon sinks influenced the design of a new law that controls its anthropogenic destruction. A comprehensive understanding of the main problems confronting farmers within their production systems regarding soil–water–plant interactions and related yield constraints is thus timely, considering it can help reduce the opening of new fields in mangrove areas. Indeed, many well-adapted production techniques [29,30] are no longer able to cope with increasing climate change phenomena and there is an urgency to co-develop sustainable recommendations with farmers aimed at restoring their land, rice yields, and livelihoods.

Research studies are needed to address the critical knowledge gap in the scientific understanding of sustainable agricultural practices that are effectively adapted to the diverse and context-specific needs of West Africa and how farmers make their choices, ensuring that they are both environmentally sustainable and effective within local settings. In this context, the overall objective of this study was to understand and evaluate soil fertility dynamics in the MSR in relation to rice production, giving prominence to existing and new sustainable management practices to induce nutritional soil improvements and reduce possible toxicity problems to empower/dress up farmers with more adaptive capabilities [31]. For that, we (1) assessed the spatial distribution of the soil fertility status; (2) assessed the relation between soil properties, nutrients, and water availability; and (3) assessed the relation between nutrient availability and yields considering context-specific preferred varieties. These assessments were integrated to contribute to understanding how experimental results (based on field conditions) explain farmers' practices and decisions, and how common factors risking production can be mitigated and/or improved.

2. Material and Methods

2.1. Study Site Characterization

2.1.1. Location and Climatic Conditions

The study area extends across two villages in the central region of Oio (Enchugal [W: 12°0′40.2″ N: 12°03′25.2″] and Malafu [W: 15°01′04.6″ N: 12°0′40.2″]), two villages in the southern region of Tombali (Cafine [W: 15°10′35.5″ N: 11°13′07.4″] and Cafale [W: 15°09′04″ N: 11°12′10″]), and in Guinea-Bissau (Figure 1a) where field research was conducted during 2021 and 2022. These regions display varying agro-ecological and climatic conditions (Figure 1b) in addition to specific agricultural practices previously identified by Garbanzo et al. [29,30], and further explored through this work. According to the meteorological data collected in 2022 from four meteorological stations established in the Malmon project's context (located at Cafine, Enchugal, Malafu, and Elalab and providing continued access to raw data) (see Figure 1b), the southern region received the highest rains between June and November with annual precipitation of 2125 mm, being August the wettest month during 2022. Temperatures were high during the entire year reaching the maximum in March with 39.3 °C and the minimum of 17.5 °C in December. For the same year, the Oio region received a total of 1410 mm; August was the month with the highest precipitation (536 mm), while temperatures reached a maximum of 42.5 °C and a minimum of 13.5 °C (Enchugal village).

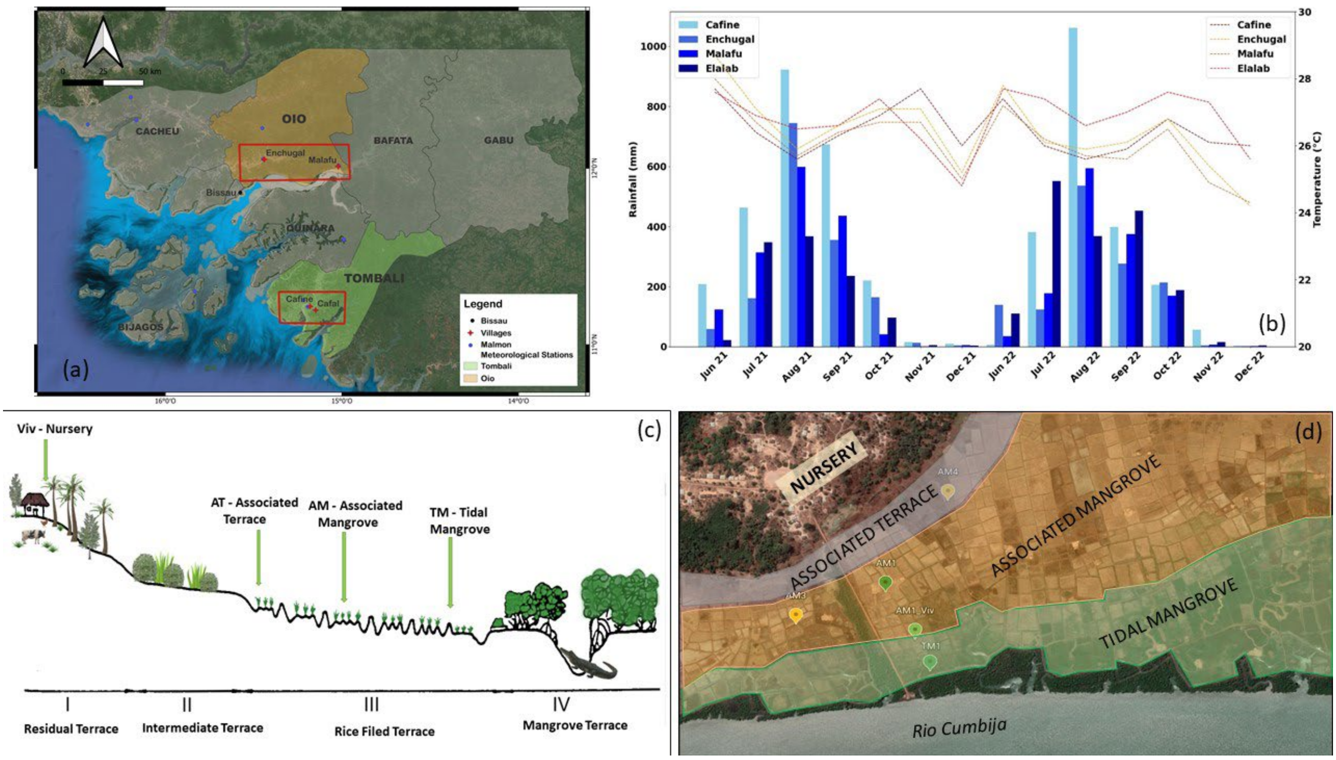

Figure 1. (**a**) General location for selected studied regions and villages; (**b**) monthly total rainfall and mean temperatures from the four meteorological stations in Cafine, Enchugal, Malafu, and Elalab for 2021 and 2022; (**c**) schematic profile of the catena and rice field terrace sub-divided in three main agroecologies; (**d**) spatial distribution and localization for selected agroecologies. Sources: (**b**) Malmon project meteorological stations network; (**c**) Merkohasanaj et al. [15].

2.1.2. Soil Management

The strategy was based on co-designing the research approach guided by the farmer's local needs and the practices they adopt to cope with specific challenges.

Balanta farmers plow their MSR fields (called Bolanhas in Kriol) with a long manual plow in two phases: the initial phase begins when the soil is sufficiently moist after the first rains [29], so farmers overturn the leftover rice straw from the previous year and the current natural green vegetation which will be the base of the new ridges. In the subsequent phase, they elevate the ridges to an average height of 40 cm (ranging from ca. 20 cm to ca. 60 cm), gathering soil from both sides of the ridge. There can be a time gap of 1 to 10 days between these phases, which significantly impacts the planting process and the nutritional development of the soil.

Adjacent to the residual and intermediate terraces, the Associated Terrace (AT) fields cover a minor portion (less than 10%) and are the last ones utilized for rice cultivation (Figure 1c,d). These fields are eventually abandoned due to downstream runoff and limited water availability, rendering them only suitable for cattle grazing. Farmers frequently state that these fields have been losing fertility in recent years due to climate change-associated extension of the dry season and higher temperatures.

The AM fields constitute 70–80% of the rice cultivation area (Figure 1c,d), featuring low ridges and occasional drainage issues, with water scarcity being a common challenge, except for some deep AMs situated near the channels that were previous river branches. Typically, land preparation, transplanting, and harvesting are conducted early in these fields, and medium-cycle rice varieties are cultivated (short-cycle varieties are also produced in the Oio region). These fields are mainly dominated by Poaceae species such as the *Echinochloa colona* (*keu* in Balanta) and Cyperaceaes species such as *Cyperus esculentus* (*miu-miu* in Balanta) are less abundant.

Farmers favor the TM fields, even though occupying only 20% of the total cultivation area (Figure 1c,d), because they own favorable soil properties influenced by tides and effective water drainage. However, in conditions of water scarcity, certain TM plots encounter significant salinization problems (Merkohasanaj et al. [15]; Garbanzo et al., [29]). Typically, TM fields feature higher ridges (40–80 cm) and dikes (ranging from 1 to 3 m) designed to shield against tidal influence. Land preparation takes place following the initial rains, and transplantation is carried out using long to medium-cycle varieties. Two main wild vegetation species are highly abundant, the *Blutaparon vermiculare* (Amaranthaceae family, *malu-cretha* in Balanta) and *Sesuvium portulacastrum* (Aizoaceae family, also called *malu-cretha* in Balanta). We found it intriguing that farmers do not perceive these species as "weeds" (in the sense of unwanted spontaneous plants that compete with the cultivated); instead, they categorize the nutritional quality of their "bolanhas" (very good, good, or bad) based on the presence of these diverse plant species in their fields. The fields recognized as highly productive are called "bolanha de *Malu-cretha*" (meaning rice fields of *Blutaparon vermiculare* and/or *Sesuvium portulacastrum*) fields or "bolanha de *Keu*" (meaning rice fields of *Echinochloa colona*), as these wild plants are indicators of good soil quality.

In the mangrove terrace (Figure 1c,d) the predominant mangrove species are *Rhizophora mangle* L., (more subject to tidal influence) and *Avicennia germinans* L. (further inland). According to farmers, these two species determine significant soil properties such as texture, porosity, color, and organic matter content, which, in turn, influence the construction and maintenance of the dikes and the time needed to drain salt and other toxic compounds from the rice fields created.

Main dikes are constructed to prevent tidal invasion, and "cordas" (strips in Kriol) are divided into plots by secondary dikes when households open new fields. However, not all plots in a "corda" belong to the same farmer, which impacts the flexibility to manage water effectively and forces coordination among neighbors for dike maintenance.

A widespread practice (according to farmers), particularly in the Oio region, involves allowing saltwater from the river to enter at the beginning of the dry period or before land preparation. This provides farmers with the advantage of early tillage, facilitates the incorporation of additional organic matter, and simultaneously aids in controlling weeds. The entrance of brackish water in the lower fields with the same aim was also frequently practiced in both Tombali (south) and S. Domingos (north) until climate change-associated delay at the beginning of the rainy season made it impossible in the northern regions with less rain and infrequent in the south. In Tombali, only hard-working farmers still use that practice in the lower plots when they see the shift from *Blutaparon vermiculare* and/or *Sesuvium portulacastrum* to undesired weeds. As these wild plants are indicators of high fertility and do not compete with the rice plants, farmers can skip plowing for several years. In this case, the entrance of brackish water is destined not only to increase fertility but also to allow the deepening of the internal canals of the plots, which will increase freshwater retention. Farmers, thus, employ various adaptive strategies to ensure a stabilized production level in times of climate change.

Furthermore, farmers classify their plot's productivity into "good", "normal", and "poor" based on the presence of certain wild plants, as above mentioned, discernible soil characteristics, such as color and texture, freshwater retention capacity, and the color (red indicates toxicity named *conra* in Balanta) and salinity of the water (assessed either through tasting or through existence or absence of temperature inversion).

2.1.3. Plant Material and Nursery Management

Aiming at increasing germplasm diversity in the study area coupled with the idea that farmers would benefit from the use of short-cycle varieties to cope with rainfall variability, farmers' saved rice varieties and purified farmers' varieties were sourced from different regions and institutions (Table 1). Each farmer tested three to seven rice varieties per agroecology in baby trials, comparing their preferred variety (used as control) with a new variety chosen based on specific characteristics such as growth cycle and salinity adaptability. During the two years of field testing, the Young Farmer Researchers (YFR) continuously co-monitored, observed, and evaluated, based on their criteria, the different tested varieties. The primary distinction between the villages lies in how nurseries are managed. Typically, in the Oio region (Enchugal and Malafu villages) nurseries are located near the households in upland soils. In the southern region of Tombali, however, nurseries are established directly in the swamp rice fields (Cafine village), or in both the uplands and swamp rice fields (Cafal, Caiquene, and Quebil villages). Considering the advantage of early planting in the case of upland nursery, the decision to adopt one of the locations or both is largely influenced by the availability of land in the uplands, the distance between the village/household and the plots, and size of the village rice fields, considering the need to avoid walking long distances for transplanting with the rice bundles on top of one's head. Nurseries' soil conditions significantly impact seedlings' quality and transplanting hill density.

Table 1. Main selected rice varieties (analyzed in this work among the 25 tested in the different trials) and specific characteristics.

	Variety (Local Names)	Growth Cycle	Species	Type and Source of Germplasm
1.	Var 5 *Selì/Mangrovia 6/N'tum*	Short (90–105 days)	*O. sativa*	*Ianda Guiné project purified farmers' variety.*
2.	Edjur	Short (90–105 days)	*O. glaberrima*	*Farmers' variety from Cacheu region*

Table 1. *Cont.*

	Variety (Local Names)	Growth Cycle	Species	Type and Source of Germplasm
3.	Etele	Short (90–105 days)	*O. glaberrima*	*Farmers' variety from Cacheu region*
4.	Caublack [P]	Medium(105–125 days)	*O. sativa*	*Farmers' variety used as control*
5.	Aferenque	Long (<125 days)	*O. sativa*	*Farmers' variety from Tombali region*
6.	Yaca Xau [P]	Long (<125 days)	*O. sativa*	*Farmers' variety used as control*
7.	Cataco [P]	Long (<125 days)	*O. sativa*	*Farmers' variety from Tombali region*
8.	Mamussu [P]	Long (<125 days)	*O. sativa*	*Farmers' variety used as control*

Note: [P] Caublack, Yaca Xau, and Mamussu are considered control varieties, being the two most preferred and widely produced by farmers.

2.2. Participatory Trials

2.2.1. Experimental Design

During the production cycles of 2021 and 2022, semi-controlled on-farm trials (co-managed with farmers) were conducted in ten Tidal Mangrove (TM) and twelve Associated Mangrove (AM) agroecologies, respectively (Figure 2a–c). The preferred rice varieties of the farmers were tested in plots consisting of 4 ridges within a 5 m area, with a random distribution of the varieties (Figure 2d). Local farmers actively participated in all trials monitoring and measurements until the harvesting.

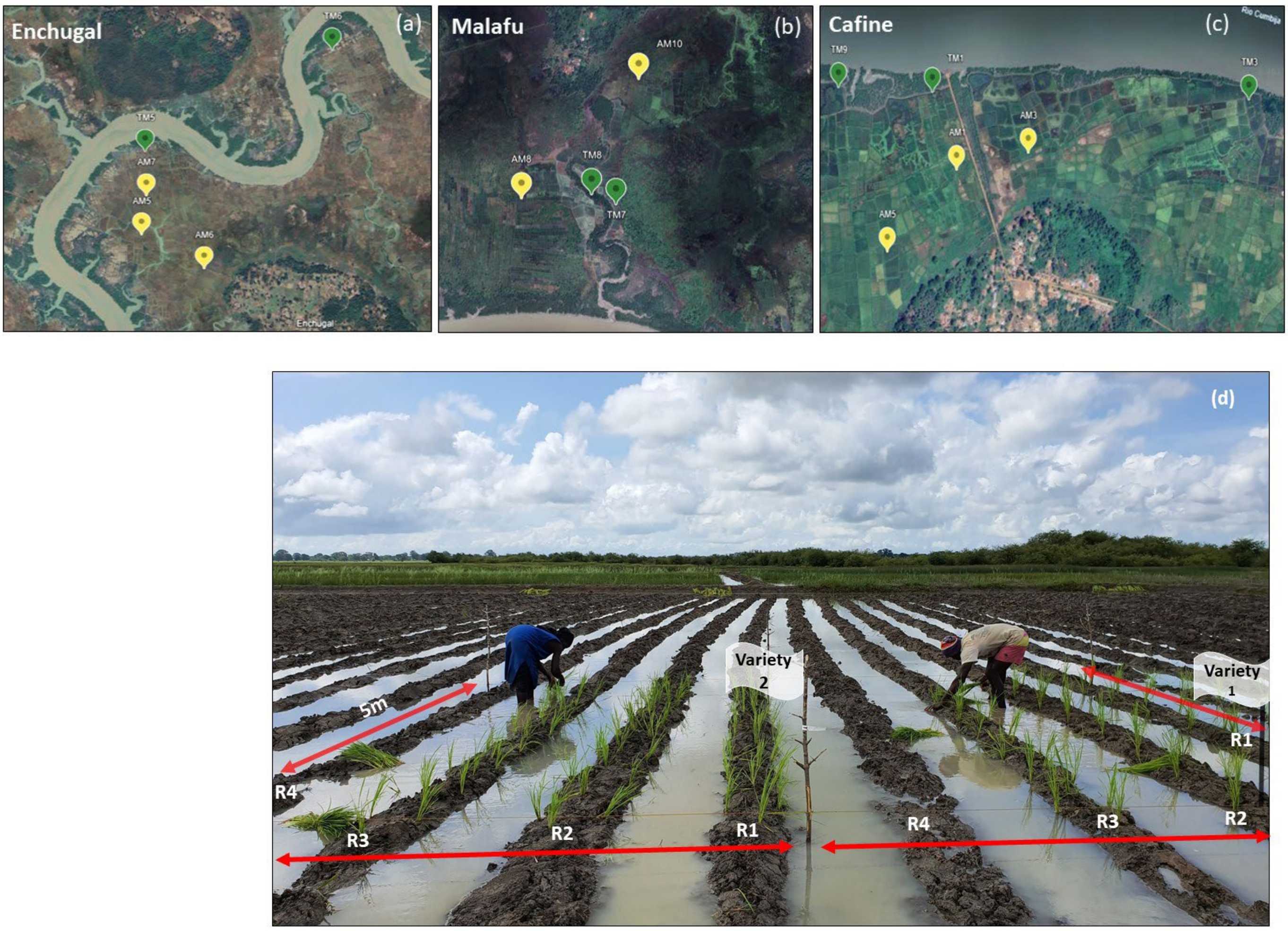

Figure 2. *Cont.*

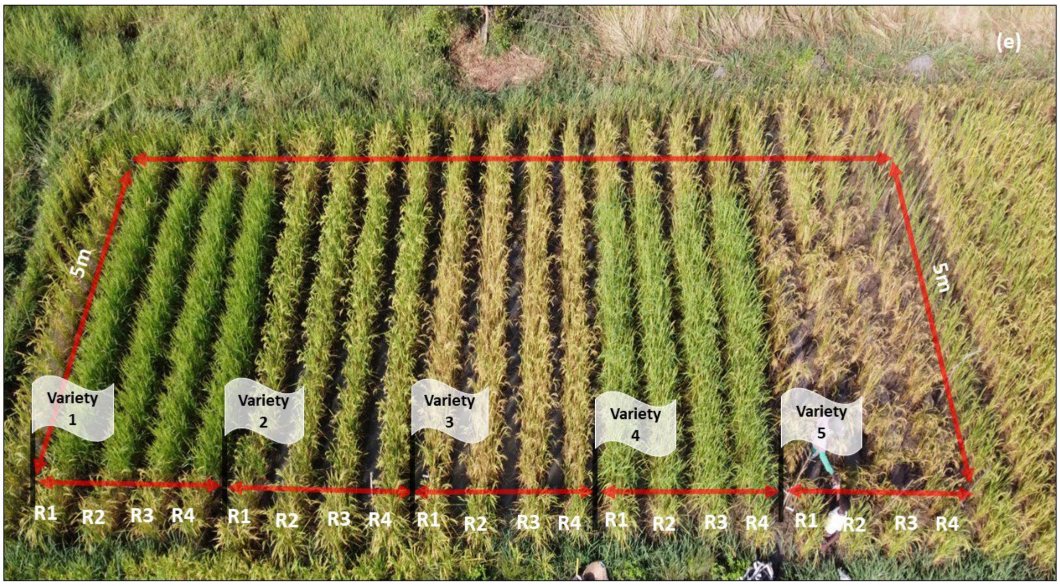

Figure 2. Trial distribution for TM and AM agroecologies for (**a**) Enchugal village; (**b**) Malafu village; (**c**) Cafine village (not all trials are represented in this photo for Cafine and Cafale villages); (**d**) Aspect of trials transplantation phase for two rice varieties in 4 ridges (R) in 5 m adjusted in farmers' conditions; (**e**) trials during grain formation (almost harvesting time) for five rice varieties; yields measurements for ridge 2 (R2) and ridge 3 (R3) for 1 m^2 (in blue).

2.2.2. Soil Sampling

Soil samples of the topsoil (0–20 cm, as this corresponds to the rice main root zone) were collected in a composite of 5 samples per approximately 30 m^2, obtaining 2 to 3 composite samples in each trial, using a conventional soil auger. A total of 380 soil samples were collected during key growing phases: 98 at T1—Sowing (July–August), 125 at T2—Transplanting (August–September), and 123 at T3—Flowering/Grain formation (October-November). Additionally, during the 2022 dry season, a special soil sampling (T0) was conducted across all experimental trials, resulting in 34 soil samples to assess soil properties under dry-aerobic conditions. Of the 248 samples collected at T1 and T2, 135 belonged to the AM trials, while 113 were from the TM trials. The remaining samples were associated with T0 and T1, which might include nurseries in AMs, TMs, or upland soils. AT soils were not selected for trials as they are mostly abandoned and not used for rice production as described in Section 2.1.2.

2.2.3. Plant Growth Sampling and Measurements

Plant growth parameters were measured and annotated during transplantation (plant height, root length, water level, number of leaves) (Figure 2d), flowering/grain formation (plant height, number of tillers, water level), and harvesting (number of panicles per plant and grain weight per m^2 in two central ridges R2, R3), meeting the soil sampling timing (Figure 2e).

2.3. Soil Physicochemical Analyses

A total of 380 soil samples (including nursery) were collected according to FAO (2021) methodology and directly measured for field pH in water, electrical conductivity (EC), and redox potential in a 1:5 soil–water solution. Then, the soils were dried and sieved in the Soil and Water Laboratory, Bissau (Direção Geral de Engenhaira e Desenvolvimento Rural) and analyzed for pH (in water (pH H_2O), EC, and Redox potential (1:5 soil-water solution) and texture analyses with the hydrometer method [32]. Soil organic carbon (SOC) and organic matter (OM) estimated through the organic carbon measured by dichromate oxidation with Tyurin method [33], total C and N by combustion mass spectrometer; P and K by Egner-Richm method [34], while base saturation (BS) and cation exchange capacity (CEC) were extracted with ammonium acetate and measured by Atomic Absorption Spectrophotometry (Thermo Helios Alpha UV/Vis Spectophotometer, Thermo Fisher Scientific, Walthman, MA, USA). In addition, Fe and Al oxides were analyzed by the ammonium-oxalate (0.2 M, pH 3.5) extraction and total exchanged acidity, Al^{3+}, and H^+ Exchange Acidity by 1N potassium chloride extraction in the Soil and Agricultural Chemistry Laboratory in Granada University (UGR) and at Soil Laboratory from the School of Agriculture of the University of Lisbon (ISA-ULisboa).

2.4. Data Analyses

The data obtained from the two consecutive years of the study were subsequently analyzed by Exploratory Factor Analyses (EFA) using Principal Component Analysis (PCA) as the extraction method and Multivariate Regression Analysis (MRA) using Phyton tools (found in the *GitHub* repository), with a standard probability level of 0.05 employed to assess statistical significance. Two different databases (both with data from 2021 and 2022) were used to facilitate the analyses:

1. In total, 283 soil samples (following the database clean-up and harmonization) across 19 soil properties. To eliminate the nursery differences between the regions, the soil database was harmonized by considering only the soil samples for T2 (transplant period) and T3 (flowering/grain formation period). To fill in missing values for specific variables like textures and Fe and Al oxides, we utilized the mean of the corresponding agroecology for imputation, leading to enhanced performance in dealing with missing data;
2. In total, 6500 records on rice growth properties and final production (5 growth properties) for 25 rice varieties in order to understand the correlation between final yields and growing parameters.

Principal Component Analysis (PCA) was used for grouping soil and growth/production variables into a few principal factors explaining the covariance in the data.

First, the factorability was tested by using Bartlett's test of sphericity (usually less than 0.05 is considered appropriate), and the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy (values above 0.6 are acceptable) [35]. Three variables from the soil database were removed (respectively, Al^{3+} and H^+ Exchange Acidity, SOC, and C/N) as there is strong collinearity with Total Exchanged acidity and C and N variables. The number of components in the PCA was selected, accepting eigenvalues > 1, which express the variance explained from each factor [36]. Key variables inside each factor were identified using the varimax rotational method [37], making the interpretation of each factor easier. We considered key variables the ones with values higher than 50% (0.5). Additionally, Pearson correlations were observed for the variables.

Two different sets of data were stratified in multivariate regression analyses (MRA), observing the relation between yields and soil properties for all tested varieties in both regions for (a) TM and (b) AM agroecologies. Means of 10 days' and 3 days' precipitations were added to this MRA considering rainfalls as a key variable influencing soil properties and rice growth. Finally, the T-test was used to check statistical differences in production.

3. Results

3.1. Soil Fertility Characterization

The overall results revealed a clear distinction in the average soil properties between the two agroecologies. TM soils showed higher average salinity levels and significantly greater nutrient levels, with notably higher concentrations of P_2O_5 and K_2O (referred to as P and K from now on) whereas no significant differences in organic matter, C, or N were observed between them (Table 2). Our results also show temporary fluctuations in the chemical properties and corresponding nutrient levels and accumulations, observed in both agroecologies. The sandy–loam–clay fraction fluctuates significantly from the dry period (T0) to the beginning (T2) and end (T3) of the production cycle. The TM topsoils are slightly acidic during T0 (pH = 5.6), but then during the production stage the acidity returns to normal levels (pH = 6.5). While salinity levels, even being extremely high during the dry season (EC = 12.2 mS cm^{-1} at T0), drop to acceptable levels for normal plant growth (EC = 2 mS cm^{-1}), probably due to sufficient precipitation, water accumulation and drainage in these agroecologies. The N-P-K availability tends to decrease from T0 to T2 and T3, probably due to nutrient leaching, while overall, the CEC does not show significant variation remaining around 30 cmol+ kg^{-1} (Table 2). The AM soils showed acidification during T0 (pH =4.7), remaining slightly acidic during T2 and T3 (pH = 5.8). Salinity in these fields falls to much lower values (EC T1, T2 = 0.8 mS cm^{-1}), while nutrient availability, namely P and K is quantified as twice lower when compared to TM, except for N that showed similar levels (≈0.2), while C accumulation slightly decrease from T0 to T2 and T3 along with the OM reduction.

The values of some variables show a high standard deviation, indicating a large dispersion of the data, which is a consequence of the intrinsic diversity of these topsoils.

The results from PCA enable us to establish relationships between different soil properties. The eigenvalues showed the presence of five factors with values > 1, explaining 69% of the total variation (Table 3). PC1 indicates positive loading for pH (0.89) having a negatively strong association with redox potential (loading: −0.84) and moderate association with exchangeable acidity (loading: −0.55). Associations with P and K content are slightly strong (loadings, respectively, 0.60 and 0.69). This component explains 20% of the total variability and is identified as an "Acidity Macronutrient component".

PC2 shows high loading values in OM (0.89) and N content (0.74), which are well associated with very high loadings in C content (0.85), indicating an "Organic component".

The PC3 groups variables that represent a "Texture component". The clay content (loading: 0.91) exhibits a negative association with the silt content (loading: −0.90), indicating a logically inverse relationship, whereas none of them appears to be significantly associated with other variables.

PC4 groups the textural sand content (loading: 0.73) with high EC (loading: 0.64) and Bases Saturation in moderate positive loading (0.58), indicating the relation between the sandy soils and the high salinity content (EC) and saturation in bases (sodium saturation as indicated by Garbanzo et al. [29]. This relation suggests a "Salinity component".

The last significant component, PC5, suggests a pronounced relationship between Fe and Al oxides (loadings of 0.76 and 0.72, respectively), while marking a weak negative association with CEC (loading: −0.48) for both variables, indicating an "Oxides component".

Table 2. Total means of soil chemical properties for 283 topsoil samples for TM and AM agroecologies and periodical means for the T0 = dry season (April), T2 = transplantation phase (August–September), and T3 = Flowering/Grain formation phase (October–November) 2021–2022. EC, electrical conductivity; RP, redox potential; OM, organic matter; CEC, cation exchange capacity; BS, base saturation; T. Ex. Acid., total exchangeable acidity.

	Sand (%)	Silt (%)	Clay (%)	pH (1:5)	EC (mS cm^{-1})	RP (mV)	OM (%)	C (%)	N (%)	P_2O_5 (g kg^{-1})	K_2O (g kg^{-1})	CEC (cmol+ kg^{-1})	BS (%)	Fe_2O_3 (%)	Al_2O_3(%)	T.Ex. Acid. (cmol+ kg^{-1})
TM—Tidal Mangrove (both regions, n = 147)																
Tot. mean	16.4	35.4	48.1	6.3	3.4	35.6	2.3	1.2	0.2	36.3	683.4	30.3	69.7	7.9	0.7	1.0
mean T0	32.8	24.2	43.0	5.6	12.2	76.4	3.1	1.3	0.2	42.1	858.6	29.2	96.6	9.1	1.0	0.4
std	9.8	12.7	8.2	0.7	10.0	44.5	0.8	0.3	0.0	20.7	307.7	9.9	9.8	3.5	0.2	0.5
mean T2	14.0	42.1	43.9	6.4	2.2	30.8	2.3	1.3	0.2	32.9	721.5	31.8	59.6	9.4	0.3	0.8
std	7.9	12.5	14.0	0.6	1.7	36.4	0.6	0.2	0.0	14.3	204.5	7.4	24.0	3.8	0.3	1.2
mean T3	7.1	32.4	60.6	6.5	2.0	27.5	2.2	1.3	0.1	37.9	590.2	29.2	71.7	6.8	0.8	1.4
std	6.0	12.9	16.9	0.6	1.5	33.1	0.6	0.3	0.0	16.0	272.9	6.6	29.7	2.5	0.2	1.8
AM—Associated Mangrove (both regions, n = 136)																
Tot. mean	12,82	44.7	42.0	5.6	0.9	72.7	2.7	1.4	0.1	6.1	350.3	27.1	43.8	6.3	0.9	2.2
mean T0	22.4	40.9	36.8	4.7	2.1	129.9	3.3	1.6	0.2	8.0	342.7	25.4	54.2	9.1	1.4	2.5
std	7.0	9.5	6.6	0.3	1.5	18.8	0.8	0.4	0.0	6.4	130.5	15.0	30.3	3.4	0.8	1.7
mean T2	9.2	47.1	43.4	5.7	0.8	67.0	2.7	1.5	0.2	4.8	379.7	28.2	31.9	5.8	0.4	2.2
std	4.4	11.9	13.3	0.5	0.5	34.4	0.8	0.4	0.1	7.0	184.1	7.7	18.2	1.8	0.5	1.5
mean T3	12.6	42.6	43.5	5.8	0.8	62.8	2.5	1.4	0.1	6.9	324.0	26.7	52.7	5.4	1.2	2.1
std	6.4	11.8	9.9	0.7	0.6	36.0	0.7	0.4	0.0	10.0	149.3	8.1.	25.1	3.0	0.5	1.3

Table 3. Principal component table and the variable loadings. Upper loadings are marked red.

Variables	PC1	PC2	PC3	PC4	PC5
Sand (%)	−0.25	0.31	−0.22	0.73	−0.24
Silt (%)	0.19	−0.20	0.91	−0.27	0.19
Clay (%)	−0.04	0.01	−0.90	−0.26	−0.07
pH (H_2O)	0.89	−0.21	0.07	−0.23	0.29
EC (mS cm^{-1})	0.29	−0.02	0.09	0.64	−0.19
Redox Potential (mV)	−0.84	0.24	−0.10	0.24	−0.28
Organic Matter (%)	−0.24	0.89	−0.01	0.09	0.03
C (%)	−0.26	0.85	0.05	−0.19	0.17
N (%)	−0.01	0.74	−0.27	0.07	−0.23
P (g kg^{-1})	0.60	−0.02	0.19	0.25	−0.07
K (g kg^{-1})	0.69	−0.04	0.06	0.30	−0.22
Cation Exchange Capacity (cmol+ kg^{-1})	0.15	0.24	−0.10	−0.13	−0.48
Base Saturation (%)	0.06	−0.09	0.04	0.58	0.01
Fe_2O_3 (g kg^{-1})	0.11	0.02	0.00	−0.15	0.76
Al_2O_3 (g kg^{-1})	0.02	0.18	0.19	−0.26	0.72
Total Exactable Acidity (cmol+ kg^{-1})	−0.55	0.29	0.12	−0.14	0.14
Explained Variance (%)	21	15	12	11	10

Bartlett Coefficient = 4010.1518803851504; KMO = 0.61951. PC = Principal Component.

The biplots generated by the PCA are provided in Appendix A Figure A1. The results confirm a clear distinction between the two agroecologies, explained by the "Acidity Macronutrient component" (PC1) (Figure 3a). This separation is explained by the positive relationship between pH, P, and K and the negative correlation with the pH and total exchangeable acidity. It is also clear that the TM soils exhibit a narrower distribution (see Figure A1a in Appendix A) in these components compared to the AMs. This result agrees with the significantly lower levels of measured P, K, and CEC, as per Table 2. Moreover, the results suggest that AM soil conditions are more heterogeneous in terms of salinity, allowing villages to differentiate (Figure 3b). PC4 (representing the "Salinity component") is associated with higher EC, BS, and Sand % in the Tombali agroecologies (note that a few samples (1%)) collected from the AM agroecology in Oio are identified as outliers (Figure 3a). Hence, the combination of PC1 and PC4 highlights a notable distinction between the Oio and Tombali regions within the AM agroecology (Figure 3b). This effect was not discernable in samples collected in TM. Zooming into the former agroecology reveals no significant differences between the Tombali villages of Cafine and Cafale, likely due to their spatial proximity. In contrast, the villages in Oio display notable variations, with Malafu, exhibiting more negative PC1 values compared to the more positive PC1 distribution observed in Enchugal (Figure 3b).

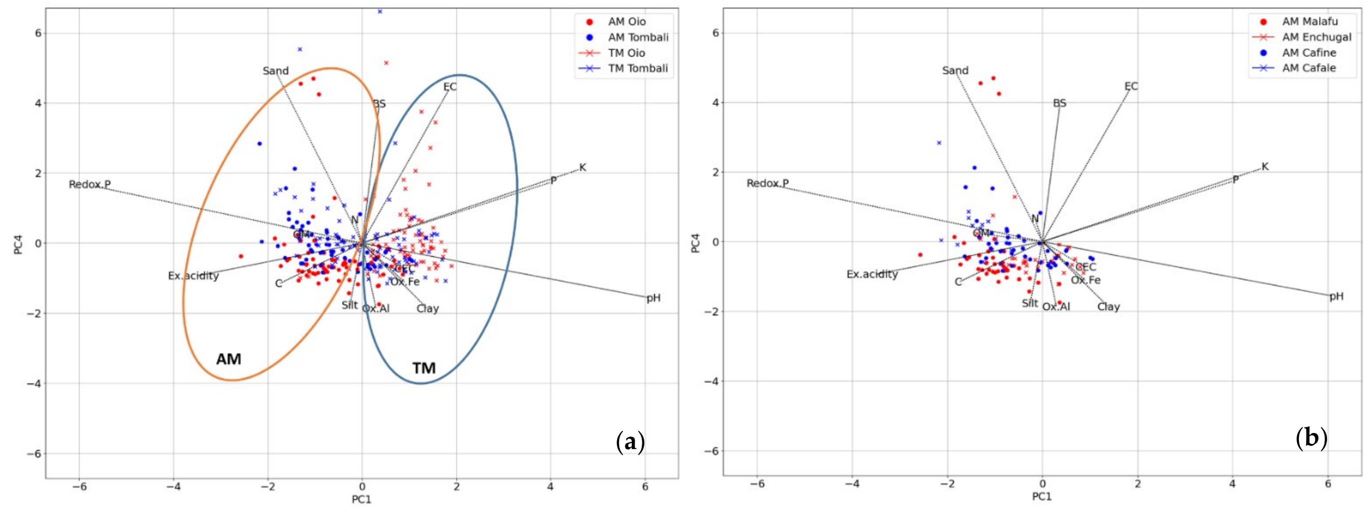

Figure 3. (**a**) biplot for PC1 vs. PC4 showing a clear separation between agroecologies; (**b**) biplot for PC1 vs. PC4 showing a distinction between regions/villages. In the later plot, TM data were hidden (find full soil biplot graphs in Appendix A).

This suggests that AM soils in this region are considerably diverse.

3.2. Growth and Yields Characterization (GY)

Aiming at understanding the influence of TM and AM soils in rice growth parameters and yield, two additional PCAs were conducted: (a) using related measurements as input (Table 4 and Figure 4); and (b) adding water availability-related data (Table 5 and Figure 5).

As shown in Table 4, when growth parameters are considered, PC1 and PC2 alone explain 60% of the total variance.

The first component (PC1) encompasses yields variable with very high loadings of yields in ridge 2 and ridge 3, being 0.90 and 0.85, respectively, jointly with a significant loading of 0.54 in plant height at transplantation (Table 4A).

The second component (PC2) is mostly explained by the no. of panicles per m² with very high loadings (1.00) (Table 4A). In this analysis, the PC1 and PC2 biplot revealed that the highest yields are found in Tombali's AMs and TMs (Figure 4). Extracted statistics (blue and orange circle, Figure 4) confirm that farmers' preferred varieties are those having the highest yields for Tombali: Yaca Xau (33.3%), Caublack (28.5%) and Mamussu (9.5%), with other varieties representing 14.2%. Few plots show high yields in Oio AMs being predominant Caublack (31.8%), and Aferenque (9.09%) with other varieties accounting for 22.7% (Table 4B).

Table 4. (**A**) Principal component table and the variable loadings for growth–production database 2021–2022. High loadings are marked in red; (**B**) Distinctive varieties with the highest score in PC1 vs. PC2 biplot (Figure 4).

(A) Variables	PC1	PC2
Plant Height 1 (cm) (transplantation)	**0.54**	−0.11
Plant Height 2 (cm) (flowering)	0.36	−0.22
Nr. Panicles (panicles per m²)	−0.02	1.00
Yield Ridge 2 (g/m²)	0.90	0.04
Yield Ridge 3 (g/m²)	0.85	0.03
Explained Variance (%)	39	21
Note: Yield = grain weight per m^2 in ridges 2 and 3.		

Table 4. *Cont.*

(B) Varieties	(%)
Yaca Xau [T]	33.33
Caublack[T]	28.57
Mamussu [T]	9.52
Cataco [T]	4.76
Aferenque [T]	4.76
Edjur [T]	4.76
Others [T]	14.29
Caublack [O]	31.82
Aferenque [O]	9.09
Others [O]	22.73
[T] = Tombali; [O] = Oio	

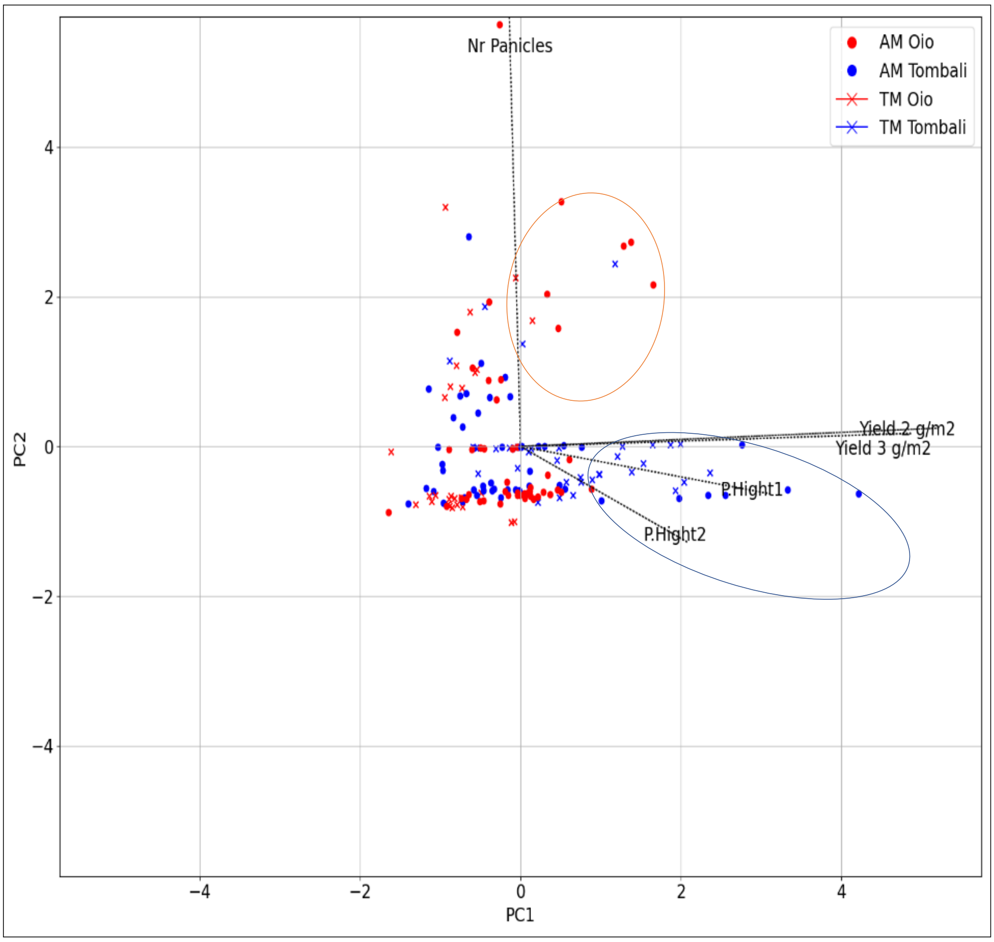

Figure 4. Biplot showing PC1 vs. PC2 samples separation based on growth parameters and yield.

Considering the direct impact of water availability on yields throughout the growing cycle, a complementary PCA was conducted.

Including water availability (assessed by levels of precipitation during transplantation and flowering and the level of the water table) provides additional information. As shown in Table 5A, the total variance explained by the four PCs is 69%. The first component (PC1) indicates four key variables with high loading being mean precipitation during transplanting (0.95) and flowering or grain formation phase (0.71), in relation to panicles number per meter square during harvesting (0.74). This component allows discussing a *Precipitation-Panicle component*.

The second component (PC2) indicates high loadings for plant height 1 and water level 1 (transplanting phase) with loadings of 0.92 and 0.98, respectively. Both variables seem to have a slightly weaker association with yield variables weight R2 and weight R3 with loadings of 0.48 and 0.51, respectively, establishing a correlation on the *Transplanting-Yields component*.

PC3 shows a positive weak association of plant height 2 (flowering phase) with the very high loadings of yields in ridge 2 (weight R2) and 3 (weight R3) showed very high loadings, 0.81 and 0.78, respectively, contributing to a *Plant high–Yield component*.

PC4 shows the direct relation between the 10 days mean and total precipitation in the last 3 days, representing a *Precipitation component*, which does not provide us with additional associations and relevant information with the rest of the variables.

Biplot combination (especially the PC2 and PC3 which contain yield variables) revealed a significant association between yield (weight R2, R3), water level (1,2), and pant height (1,2) parameters, given the critical role of water availability throughout the growing cycle and its direct impact on yields.

Table 5. (**A**) Principal component table and the variable loadings for growth–production database 2021–2022. Marked in red high loadings and in orange moderate loadings; (**B**) Distinctive varieties with the highest score in PC1 vs. PC3 biplot (Figure 5a); (**C**) Distinctive varieties with the highest score in PC2 vs. PC3 biplot (Figure 5b).

(A) Variables	PC1	PC2	PC3	PC4
Plant Height 1 (cm) (transplantation)	−0.12	0.92	0.22	0.09
Water Level 1 (cm) (transplantation)	−0.07	0.98	0.18	0.04
Mean Precipitation 1 (mm) (transplantation)	0.95	0.02	−0.16	0.09
Total Precipitation 1 (mm) (transplantation)	0.77	−0.15	−0.11	−0.07
Plant Height 2 (cm) (flowering)	−0.28	0.05	0.48	−0.14
Water Level (cm) (flowering)	−0.01	0.02	0.15	0.09
Mean Precipitation 2 (mm) (flowering)	0.71	0.07	−0.08	0.74
Total Precipitation 2 (mm) (flowering)	0.05	0.08	0.03	0.79
Nr. Panicles (panicles per m²)	0.74	−0.07	0.04	0.12
Yield Ridge 2 (g/m²)	0.11	0.48	0.81	0.12
Yield Ridge 3 (g/m²)	0.09	0.51	0.78	0.17
Explained Variance (%)	23	19	17	11
Note: Yield = grain weight per m² in ridges 2 and 3. Mean Precipitation (mm) is the average of the last 10 days' rainfalls; Total Precipitation is the sum of the last 3 days' rainfalls.				
(B) Varieties (Figure 5a)	**(%)**			
Caublack	28.57			
Yaca Xau	28.57			
Mamussu	14.29			
Cataco	9.52			
Aferenque	4.76			
Others	14.29			
(C) Varieties (Figure 5b)	**(%)**			
Caublack	20.83			
Yaca Xau	12.5			
Edjur	12.5			
Cataco	8.33			
Mamussu	4.17			
Others	20.83			

Extracted statistics (blue and orange circle, Figure 5) reveal that the plots with the highest yields correspond to the varieties identified by farmers as their preferred choices being Caublack, Yaka Xau, Edjur, and Cataco, each within their respective agroecological contexts (Figure 5b, Table 5C). This underscores the importance of local knowledge in selecting the most suitable varieties for specific conditions and associated management practices.

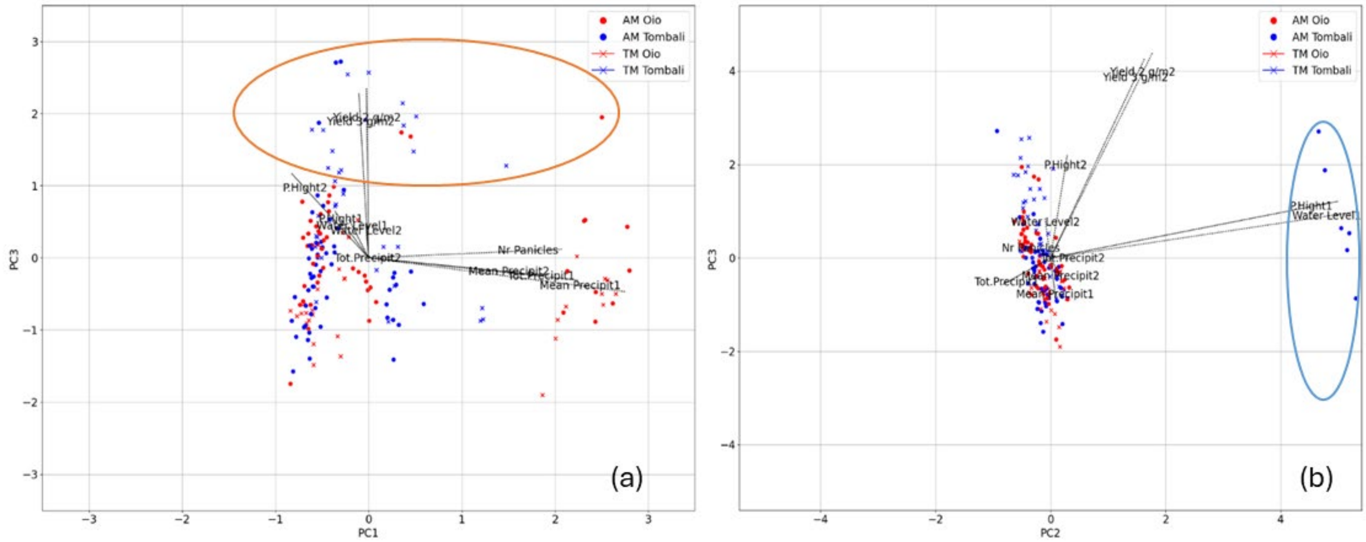

Figure 5. Biplot showing: (**a**) PC1 vs. PC3 and (**b**) PC2 vs. PC3 samples separation based on growth parameters and water availability; The orange circle highlights a significance for yield 2 g/m^2 and yield 3 g/m^2 in PC3 variables, while the blue circle highlights a notable association for P. Hight 1 and Water level 1 in PC2 variables.

3.3. Yields in Response to Soil Fertility Status (SFS)

I. Prediction of yields based on soil properties

Spearman's bivariate correlation analysis revealed a strong correlation among the Organic Component, as well as a positive correlation between the "Acidity macronutrient component", base saturation, and CEC (Figure 6). Conversely, yield correlation with soil properties appeared weak in all cases, exhibiting positive correlation patterns with the Organic component but negative with the Acidity macronutrient component, along with a weak positive correlation with the precipitation variables.

To streamline the Multivariate Factor Analysis (MFA), we included only the variable that most accurately and directly reflects the rice yields (the grain weight per m^2) and the water availability (mean 10 days precipitation). The MRA showed a very strong predictability capacity as the model explains 81% of the variance (R2) in the case of TM agroecologies being OM, N, and K content strong predictors for yields (Table 6a). Likewise, CEC is shown to be a good predictor (p-value = 0.018, t = 2.220) (Table 6a).

In the case of AM agroecologies, the model explains just 56.9% of the total variance where the sand content, pH, mean precipitation, again OM, the N and K content, and as well the Fe oxides concentrations were the soil variables that more accurately predicted yields for this agroecology (p-values < 0.05) (Table 6b).

These results indicate that the model predicts yields more accurately for TM (81%) compared to AM (57%). This difference could be attributed to the greater soil variability and instability factors in AM agroecologies, as confirmed in the previous sub-section.

Also, the predictability capacity of TM is based just on five variables (Clay and OM %; N; K and CEC) while AM is based on five variables (sand, pH, Mean Precipit, OM, N, K, and Fe_2O_3). Interestingly, the model precisely identified for AM the most limited variables as pH, precipitation (water), and Fe oxides (Table 6a).

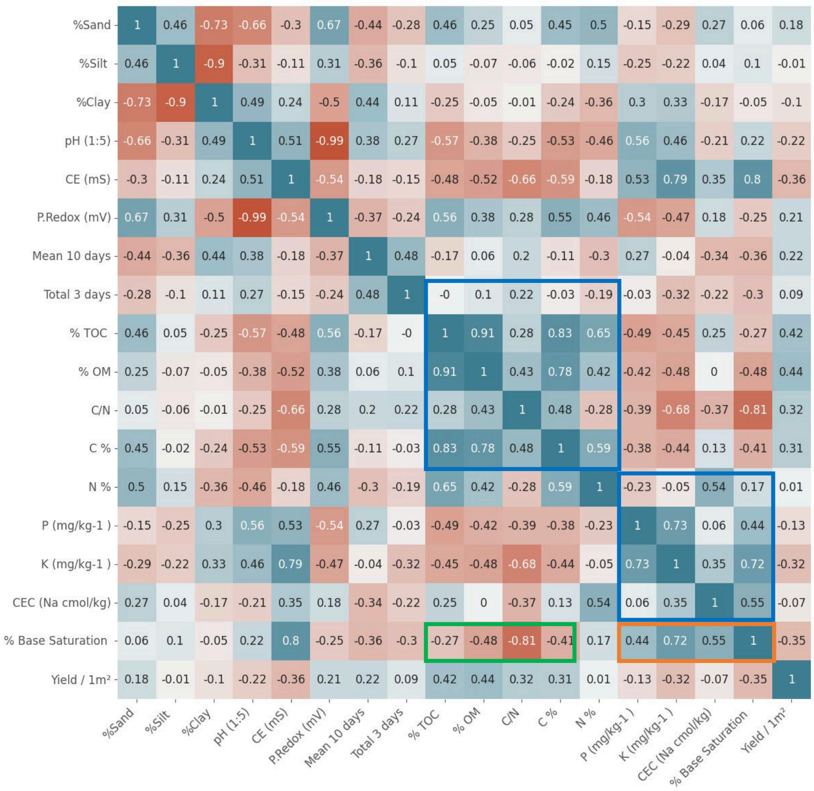

Figure 6. Overall, Spearman's bivariate correlation matrix for soil properties during 2021 and 2022 from blue (positive correlation; the darkest the closest to 1) to red (negative correlation; the darkest the closest to −1); green rectangle showing yield's positive correlation with "organic component"; orange rectangle showing yield's negative correlations with "acidity macronutrient component"; blue rectangle showing correlation within components.

Table 6. MRA results between yields and soil properties for (**a**) overall TM agroecologies; and (**b**) overall AM agroecologies. Only the variables showing significant loadings are included.

Variables	*p*-Value < |t|	T
(a) N = 61, R^2 = 0.81/TM-cases		
Clay (%)	0.024	−2.326
OM (%)	0.000	4.914
N (%)	0.003	3.128
K (g kg^{-1})	0.007	2.837
CEC (cmol kg^{-1})	0.018	2.440
(b) N = 94, R^2 = 0.569/AM-cases		
Sand (%)	0.000	−15.27
pH	0.016	−2.457
Mean Precipitation (mm)	0.000	4.318
OM (%)	0.000	4.406
N (%)	0.034	2.160
K (g kg^{-1})	0.027	2.255
Fe_2O_3 (g kg^{-1})	0.000	−3.926

II. Performance of the farmers' preferred varieties per agroecology in relation to Soil Fertility Status

A subset of the varieties selected by the farmers as being of their preference were tested for yields in the two agroecologies and the statistical descriptive results showed differences in the yields (Figure 7). Long cycle varieties such as "Yaca Xau, Mamussu, Cataco" yielded better in TM agroecologies. The exception was "Aferenque" that shows better yields in AM agroecologies. However, this variety had much lower yields 162 g/m^2 in comparison to the first ones yielding 215, 240, and 194 g/m^2, respectively, in AMs. The same varieties yielded much better in TM agroecologies, with, respectively, 232, 263, and 190 g/m^2. Accordingly, farmers in the TM fields predominantly opt for these varieties. This choice is influenced not just by the extended cultivation cycle and the long-lasting water availability in TM agroecology but also because, at the same time, these fields ensure good yields owning very good soil nutritional levels.

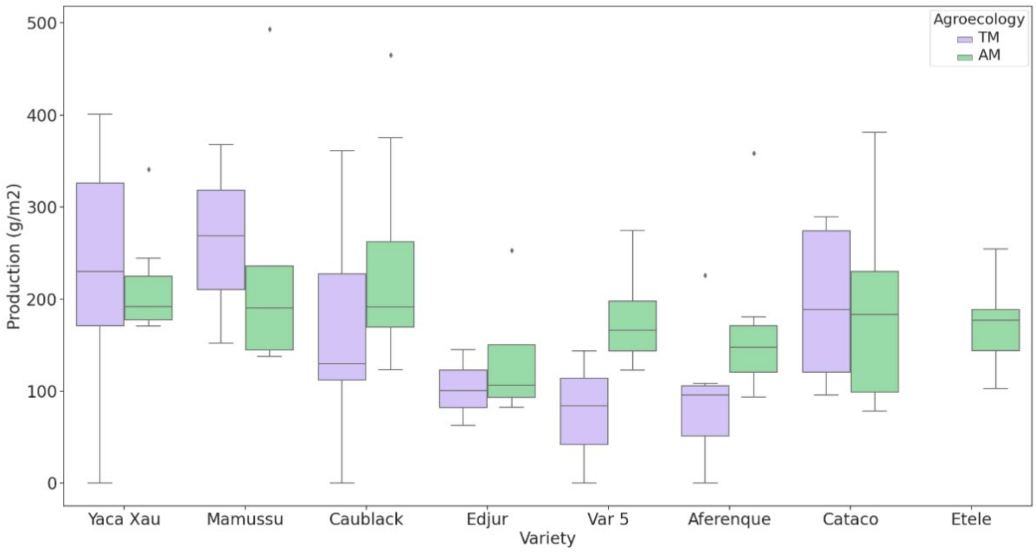

Figure 7. Boxplot of yields for main tested varieties for TM (purple) and AM (green). Note: Etele was tested just in Oio AMs.

TM soils are reported to ensure a rich pool of organic matter and good macro-nutrient concentration especially of P and K, while N accumulations are not a limitation (see Figure A2a in Appendix B for TM agroecologies). Despite this, acidity (pH) and salinity (EC) conditions are not limiting factors for good yields as maximum levels do not exceed 2 mS cm^{-1}. However, specific cases such as the TM plot in Enchugal village where EC levels reached 20 mS cm^{-1} during the dry season, 7 mS cm^{-1} during transplantation, remaining around 6 mS cm^{-1} during flowering, caused total production losses for all tested varieties (Yaca Xau, Caublack, Aferenque, Var 5).

Medium-cycle varieties similar to the highly preferred as the so-called "Caublack" are very few. This variety perfectly adapts in both agroecologies, although production is slightly higher in the AM (228 versus 170 g/m^2).

However, good soil nutritional pools in AMs are not assured. As seen, these agroecologies generally have a low content of macronutrients, especially P and K (see Figure A2b in Appendix B for the AM agroecology). Conversely, OM, C, and N content are quite similar even slightly higher than TM. Short cycle varieties as "Var. 5" and "Edjur" showed to better adapt at AM conditions as saline conditions are not preferable from these varieties which had quite low performance with yields not exceeding 80 g/m^2 in TM, while in AM "Var. 5" yielded 180 g/m^2.

III. Yields among regions and specific cases identified

Our results showed that the Tombali region allows better yields compared to Oio, with averages of 220 g/m^2 and 156 g/m^2, respectively. T-test analyses confirmed that these differences are statistically significant (Table 7).

Table 7. T-test results for yields between regions and agroecologies.

		Mean	Std.	St. Error Mean	95% Conf. Interval of Difference		t	df	Sig. (2-Tailed)
					Lower	Upper			
T-test 1	**TM—AM**	**25.29**	**127.89**	**13.05**	**−0.617**	**51.20**	1.93	95.0	0.055
T-test 2	Reg 1—Reg 2 [1]	70.64	143.84	11.82	47.274	94.00	5.97	147.0	0.000 *
T-test 3	TM—AM [2]	−17.91	137.50	13.96	−45.631	9.79	−1.28	96.0	0.202

* Significant level at $p < 0.05$. [1] Reg 1 = Oio, Reg 2 = Tombal; [2] TM-AM for 3 most preferred farmer varieties.

Differences in yields between regions are attributed to variations in soil nutrient pools and water availability especially for AM agroecologies. In the southern region of Tombali, the average yields for all tested varieties in TM agroecologies were around 259 g/m^2, whereas in Enchugal and Malafu village yields were, respectively, 104 and 110 g/m^2 (Table 8). This suggests that TM fields in the Oio region are more susceptible to limiting soil and agroclimatic processes. While the AM agroecologies in Tombali yielded an average of 188 g/m^2—lower than AM in Enchugal and Malafu with yields of 209 and 192 g/m^2 respectively, and probably attributed to the very low yields some varieties such as Edjure, Etele, and Cataco—had, during 2022, yields between 70 and 85 g/m^2 (Table 8), while average yields for 2022 did not exceed 150 g/m^2 (significantly lower compared to 2021 (226 g/m^2).

Table 8. Average yields per village for 2021 and 2022 per agroecology.

Region/Village	Yields 2021 (g/m^2)	Yields 2022 (g/m^2)	Average Yields (g/m^2)
TM Enchugal	103.8	105.69	104.3
TM Malafu	116.88	102.28	110.0
AM Enchugal	234.09	185.01	209.5
AM Malafu	206.07	178.93	192.5
Average Oio	**169.06**	**142.98**	**156.02**
TM Cafine-Cafale	246.26	272.41	259.33
AM Cafine-Cafale	226.07	150.0	188.0
Average Tombali	**236.17**	**211.12**	**223.64**

4. Discussion

Low-input rice-cultivation systems (as the MSR studied in this work) define the nutrient-supplying capacity either by inherent soil nutrient pools or through the application of fertilizers, which are less than the amount and rate required by the rice plant to reach attainable grain yields (t ha^{-1}), when other inputs or characteristics (e.g., drought, pest and diseases, Fe and/or Al toxicity, low-CEC, low-pH) are not yield limiting [38]. One or more nutrients may act as rate-limiting variables, especially in high acidity soils where in Fe/Al toxicity, the P and K absorption by the plant is slowed down and limited.

The occurrence of nutrient enrichment is generally from the upland to the fresh water to the mangrove area, respectively, from the upland nurseries to the AT—Associated Terrace to the AM—Associated Mangrove and to the TM—Tidal Mangrove; this is caused by the transport of nutrients and soil particles from the higher to the lower parts of the catena and due to the differences in soil moisture availability and tidal upwelling which brings more nutrients to the TMs. During the production period, intense rainfall and runoff from the upper part of the catena bring large amounts of sand to the rice fields, which later settle into the lower layers. Additionally, significant quantities of silt and clay remain suspended (while sand deposits) in the submerged paddies, which could account for the high levels of sand observed, particularly during the dry season, potentially amplified by an overestimation from the hydrometer extraction method [39]. The structure is generally good for the rice root zone, while tillage and drainage characteristics and permeability to water are much better than those of non-saline soils (AMs) [29].

The implication that TM plots do not have acidity limitation means that an increase in pH improves the CEC and minimizes the activity of acidity and hence the performance of the rice crop. In high acidity plots (as the AM agroecologies in this case), waterlogged conditions can be improved by reducing the sand content which will minimize acidity accumulation and increase the nutrient retention [4]. In AM fields, a very quick boost in organic matter occurs during the growth of high densities of *Poaceae* and *Cyperaceae* plants at the onset of the first rains, along with the dried rice straw from harvested rice crops, inducing significant organic matter and N input. Even though AM soils have higher organic matter accumulations, we observed soils with low base saturation and low CEC possibly associated with the high Fe and Al oxides concentration as well as low water availability to dissolve and neutralize them, even in some cases the jarosite formation in the topsoils. An abundance of green vegetation is not always beneficial as farmers often struggle with strong weed invasion. In TM fields, the weed competition is not as strong due to salt water intrusion during the dry season, a practice used by the farmers to control weeds [40]. Noticeably, since less than 10 years ago, a small number of farmers started hiring tractors to plow some of their AM fields, and more recently a few motor-cultivators, apparently with good results. However, the attempts of the Ianda program to introduce tractor plowing in TM fields caused the dramatic invasion of wild plants that compete with rice, forcing farmers to use herbicides for the first time. Furthermore, the impact on soil medium-term fertility, water use efficiency during long dry spells between rain events, soil compaction, and other potential drawbacks of mobilization with a tractor have never been scientifically assessed so far. As previously highlighted, the TMs exhibit superior physicochemical properties, making them the preferred choice among farmers, especially in the southern region of Tombali. Consequently, they are often the first to be cultivated and sown to "ensure food security." However, in regions like Oio, particularly in years of limited rainfall, TM fields with high salinity and acidity showed poor yields (not exceeding 107 g/m^2). A common practice employed by farmers is the use of "saltwater" prior to the growing season to leach out the acidic–sulfidic compounds. Despite this practice, success has been limited, even with external support from local NGOs whose objectives often differ from those of the farmers (authors observations).

Consistent with our observations and farmers' testimonies, recent years have witnessed significant anomalies in the distribution and intensity of rainfall [41]. Prolonged dry spells lasting for several days, followed by sudden heavy rainfall events, exemplified by the occurrence on 29 August 2021, when, in Malafu village, precipitation reached 440 mm. These abnormal climatic events have a significant impact on rice production for the country's small farmers [42]. Changes in precipitation patterns frequently exacerbate acidic conditions, significantly restricting the availability of macronutrients such as phosphorus and potassium. In particular, phosphorus availability is severely limited in soils with a pH below 5.5, where its fixation becomes highly constrained. Moreover, in more AM acidic soils, the leaching of phosphorus through runoff is accelerated, leading to substantial losses of this nutrient [43]. Varieties tolerant to low-phosphorus conditions, distinguished by their robust tillering capacity and sustained photosynthetic productivity throughout the growing season by developing a strong root zone, suggest that low-phosphorus environments may enhance phosphorus transfer to the grain, thereby mitigating yield losses [44].

However, in these agroecologies, farmers navigate a complex and dynamic social-ecological system marked by contingency and uncertainty, where risk is inherent, and their decision-making is crucial for their subsistence.

Thus, farmers' critical observation of a variety of characteristics determining selection and adoption is crucial [17,45]. As observed, varieties such as Aferenque demonstrated higher yields in AMs compared to TMs, indicating its need for higher water levels. Farmers have long observed that Aferenque's exceptionally long growth period requires a sustained water supply. Conversely, short-cycle varieties like Edjur and Var 89 have been eliminated in regions like Oio. These varieties mature quickly, becoming vulnerable to bird attacks during periods when farmers cannot organize "young bird guardians" (young children) to protect the fields [46]. Additionally, short-cycle varieties, which could address food shortages before harvest, present social challenges: farmers who grow them are often obligated to lend rice to family and neighbors without compensation. This dynamic further limits the adoption of short varieties. Importantly, the varieties with the highest yields are those preferred by farmers, underscoring the depth of their local knowledge. This insight emphasizes the indispensable role of farmer expertise in selecting the most suitable varieties for specific conditions and associated management practices.

Commonly, farmers in Oio opt for medium-cycle varieties, such as the Caublack, which become a "safety option" because it always ensures a satisfactory production under different fields (being AM or TM, and/or good fertility or normal fertile soil, limiting salinity) and precipitation conditions. In the Oio region (village of Malafu), farmers identified one of the newly tested varieties, Var. 20, a purified, nearly medium-cycle variety similar to Caublack, which showed excellent adaptability to the water-limited AM fields. With timely planting, this cultivar is expected to reach maturity before water shortages begin.

There is a wide range of new cultivars that have been introduced and selected by farmers based on certain characteristics such as digestion time, grain swelling capacity during cooking, taste, yield, ease of threshing, and husking by hand, among others [17]. However, only a few studies evaluated cultivars introduced through informal channels by farmers in relation to "modern" varieties introduced by development agents for their adaptability to drought, salinity, acidity, diverse land topographies, and biological factors [47–49]. Despite Dalton & Guei's [50] assertion that WARDA/African Rice Centre Research has successfully developed higher-yielding varieties, the same authors recognize that this does not apply to the mangrove ecology (2003: 370). Additionally, a survey conducted by one of the authors on 770 farmers in 15 villages of S. Domingos, Oio, and Tombali revealed that few, if any, improved varieties were being cultivated. In relation to pests and disease presence, there is recent research evidence that traditional storage facilities used in these particular agroecosystems provide good quality seeds [51].

Nevertheless, tackling the full complexity of the issue and developing effective solutions remain challenging. Therefore, mitigation strategies must not only account for the site-specific physicochemical, biological, and topographical characteristics, but also prioritize and integrate farmers' expertise and local knowledge as critical components.

5. Conclusions

In Guinea-Bissau, mineral fertilizers are often inaccessible due to low incomes and market issues. Agroecological solutions, however, can enhance resource efficiency, supporting sustainable rice production without harming ecosystems or human health. However, is sustainable intensification of rice production possible in these agroecologies? The goal should be to balance intensification and conservation, relying on local knowledge to co-develop climate-adaptive, diverse practices while minimizing mangrove degradation.

Maintaining and enhancing soil organic matter is crucial for sustaining soil fertility, as it improves nutrient retention, increases water-holding capacity, and supports soil biodiversity. However, this can be challenging in low-input agroecosystems. Nevertheless, practices such as early planting, reducing plant density, crop rotation, intercropping, the use of animal and green manures, fallowing, and reduced tillage offer promising and feasible solutions for farmers.

The very complex and highly vulnerable mangrove swamp rice production system needs increased adaptability to the changing rainfall patterns, increases in air and soil temperature, and sea level rise; thus, agricultural practices should be tailored to the diversity of agroecological conditions. The significant spatial-temporal variability in rainfall distribution patterns profoundly influences the soil–water–plant interactions along the catena. In this context, yearly and localized adaptations of the agricultural calendar and the available water distribution are a key strategy, together with the use of medium to short-cycle varieties. Furthermore, the comparative analysis of certain biophysical properties across study sites has enabled the identification of specific soil fertility characteristics that either hinder or promote rice growth and productivity. By combining this information with farmers' insights into soil conditions and rice variety traits, more effective strategies for site-specific adaptability can be developed.

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Data Availability Statement: The original contributions presented in the study are included in the article's Appendices A and B. Further inquiries about primary data can be directed to the corresponding author/s.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

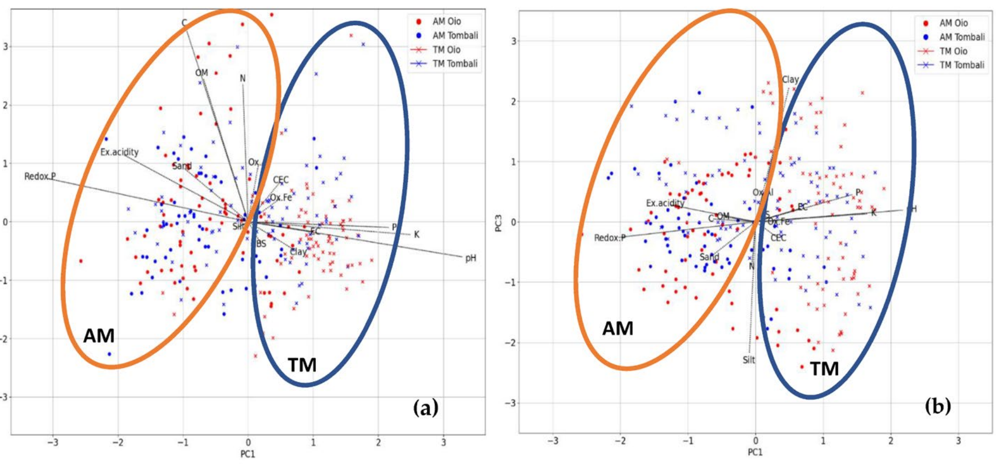


Figure A1. *Cont.*

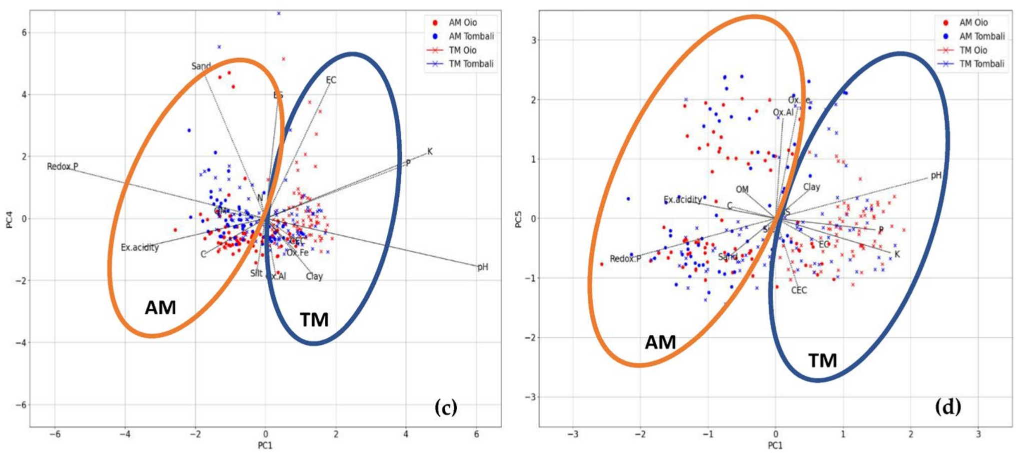
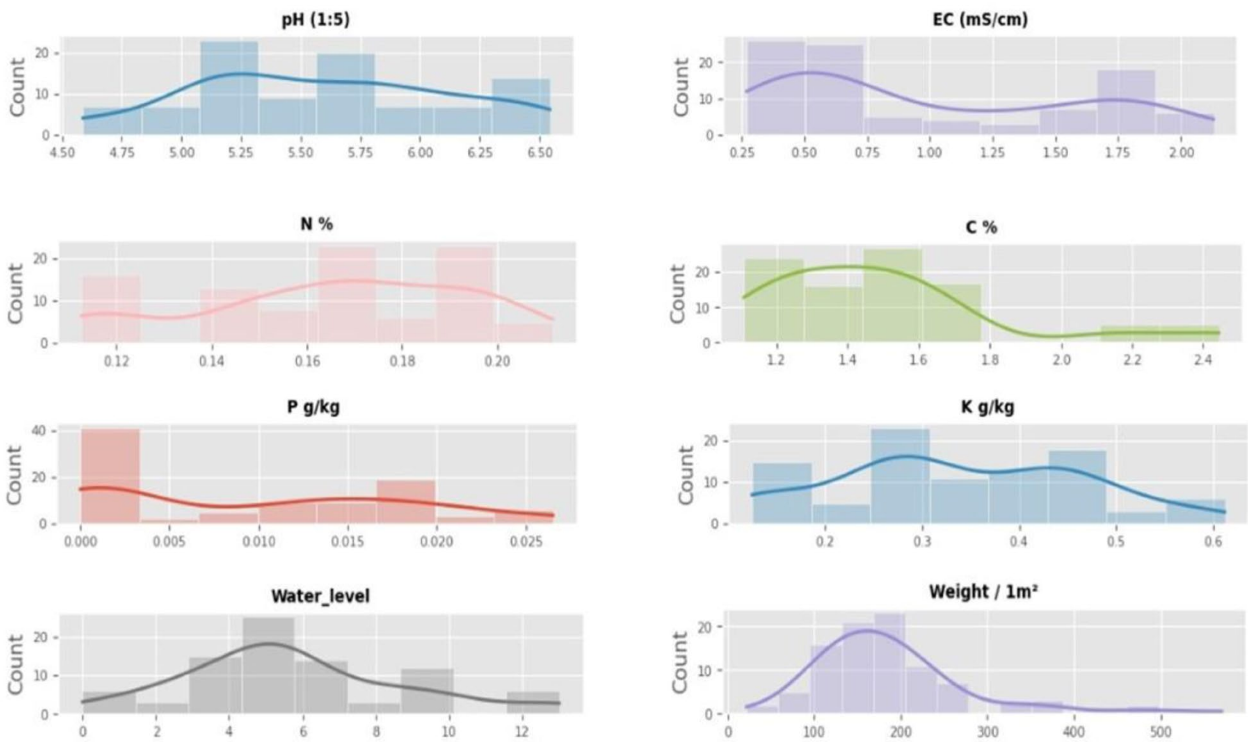


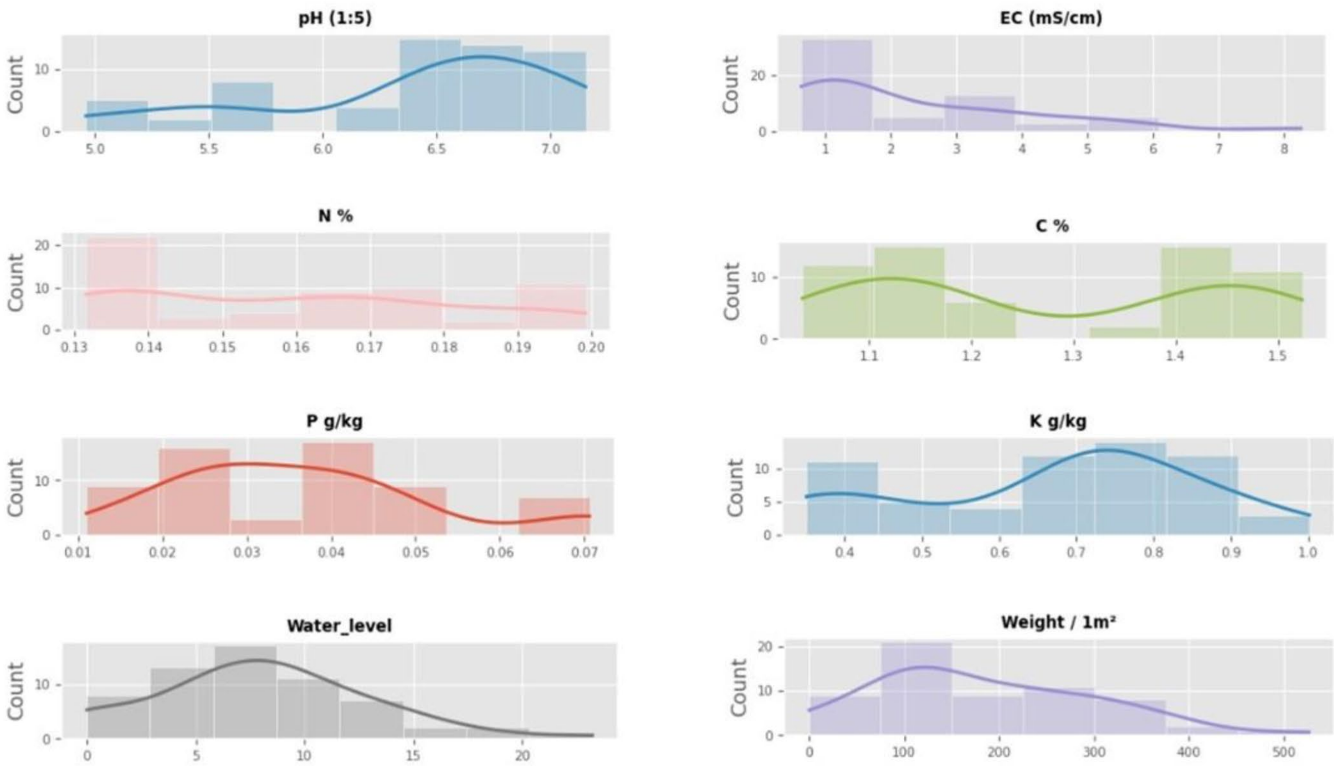
Figure A1. Biplot graphs for soil principal component (PC) combinations: (**a**) PC1 vs. PC2; (**b**) PC1 vs. PC3; (**c**) PC1 vs. PC4 and (**d**) Pc1 vs. PC5.

Appendix B



(**a**) TM—Tidal Mangrove

Figure A2. *Cont*.



(**b**) AM—Associated Mangrove

Figure A2. Numerical distribution for key soil properties, macronutrients, water level, and yields for (**a**) TM; and (**b**) AM 12 for overall MRA (2021 and 2022).

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