Catena 256 (2025) 109131

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil physicochemical characterization and suitability assessment for the coastal mangrove swamp rice production system in Guinea-Bissau

Matilda Merkohasanaj [a,c,*], Gabriel Garbanzo [b,c], Nuno Cortez [a,e], Francisco José Martín Peinado [g], Anna Andreetta [h], Cristina Cunha-Queda [c,d,f], Marina Temudo [a,d,f]

[a] Forest Research Center (CEF), School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal
[b] Soil Physics and Land Management Group, Wageningen University, 6700 AA Wageningen, the Netherlands
[c] Linking Landscape, Environment, Agriculture and Food (LEAF) Research Unit, Instituto Superior de Agronomia, Universidade de Lisboa 1349-017 Lisboa, Portugal
[d] Laboratory for the Sustainability of Land Use and Ecosystem Services (TERRA) Associated Laboratory, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[e] Departamento de Recursos Naturais, Ambiente e Território (DRAT), Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[f] Departamento de Ciências e Engenharia de Biossistemas (DCEB), Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal
[g] Departamento de Edafología y Química Agrícola, Facultad de Ciencias de Universidad de Granada, Campus Fuentenueva s/n, 18071 Granada, Spain
[h] Dipartimento di Scienze Chimiche e Geologiche, Università degli Studi di Cagliari, Cittadella Universitaria, Blocco A, 09042 Monserrato, Italy

ARTICLE INFO

Keywords:
West Africa
Soil taxonomy
Nursery topsoils
Soil suitability assessments
Soil mineralogy
Soil physicochemical properties

ABSTRACT

The mangrove swamp rice (MSR) agroecologies are widely acknowledged as crucial for rice production in West Africa, particularly in Guinea-Bissau. However, the optimal functionality of soil–water dynamics for rice cultivation, is constrained by poor soil fertility, waterlogging condition, or high soil salinity. Climatic variability, including unpredictable rainfall, droughts, and extreme weather, exacerbates these issues. Additionally, economic and social factors, including limited access to resources, labor shortages and market instability, further hinder farmerś ability to adapt, increasing mangrove swamp rice production (MSRP) vulnerability, threatening yields and food security. Soil characterization and suitability assessment serve as the foundational steps to investigate, describe, and identify constraints that small-scale farmers face daily in their production activities. In this study, soil profiles and nursery topsoils were described, sampled, and analyzed between 2022 and 2023 in three coastal areas and four villages of Guinea-Bissau, serving as study cases: Elalab (North), Malafu and Enchugal (Center), and Cafine (South). The physicochemical properties of soil were analyzed in the laboratory, and then subsequently utilized for classification and suitability assessment. Results revealed that soil profiles in the northern region exhibit structural limitations and low nutrient levels [nitrogen(N), phosphorus(P), potassium (K)] due to high sodicity concentration (> 5 cmol (+) kg^{-1}), which consequently limit rice growth and yield. Conversely, soils in the southern and central regions show significant acidification and salinization, induced by reduction conditions and jarosite formation. Shallow nursery upland soils (Oio region, center) exhibit low nutrient content and water retention capacity, restricting seedling root growth. In conclusion, the establishment of enduring and adaptable strategies for innovative soil management practices in MSRP demands bridging farmers' traditional agricultural knowledge and practices with scientific insights. Innovations will be produced through the systematic collaboration between experts, scientists and farmers, who will share observations, experiences and knowledge to foster the development of nature-based solutions.

* Corresponding author.
E-mail address: mmerkoh@uma.es (M. Merkohasanaj).

https://doi.org/10.1016/j.catena.2025.109131
Received 1 May 2024; Received in revised form 10 April 2025; Accepted 5 May 2025
Available online 9 May 2025

1. Introduction

In the coastal areas of West Africa, mangrove swamp rice production (MSRP) stands as a unique agricultural system. Established in previous saline soils, MSRP fields are highly efficient in using freshwater due to limited mechanical irrigation resources (Balasubramanian et al. 2007, Andriesse and Fresco, 1991). In Guinea-Bissau (GB), three distinct rice production systems exist: upland, inland valley (freshwater swamp), and mangrove swamp, with the latter being the most productive (Temudo and Santos, 2017; Temudo et al. 2015; Marzouk, 1991; Mota, 1954). The upland low rice productivity is caused by limited nutrient availability, and the constraints of rainfall collection in freshwater swamp fields, farmed by women with no water management infrastructures (Linares, 1981). Consequently, farmers prefer rice cultivation in former mangrove areas to ensure food security by coastal farmers (Temudo et al., 2015).

Mangrove swamp rice fields are defined as sub-ecosystems susceptible to both drought and flooding, falling within the wetland rice ecosystem (Balasubramanian et al. 2007). This system is the result of anthropogenic alteration of mangrove landscapes, involving the clearing of the forests and the building of dikes to establish plots for freshwater harvesting (e.g., Marzouk, 1991). Due to tidal influences, salinity is very high, especially in the plots closest to the main dike. For this reason, MSRP depends on timely and regular rainfall distribution. Topography is a key factor in soil genesis (Buol et al. 2011), and the building of MSR fields induces rapid transformations in the soil. The creation of dikes for cultivation obstructs the accumulation of alluvial sediments carried by the brackish water (Mota, 1954). This disturbance promotes rapid soil oxidation under aerobic conditions, fostering active geochemical alteration within the soil profile (Sylla, 1994; Marius and Lucas, 1982). Consequently, these changes often lead to soil acidification, pyrite formation, and iron solubilization, resulting in potential toxicity for plants (van Oort, 2018, Sylla et al, 1995; Hesse,1961). These geochemical processes primarily occur in newly created plots ("Bolanha nobu" in Kriol).

Mangrove forests of Guinea-Bissau are dominated by *Avicennia germinans* and *Rhizophora* sp., especially *R. mangle*. Avicennia sp. trees have superficial roots which are believed to reduce iron sulfides and consequently the acidity potential; on the contrary, *Rhizophora* sp. have dense and deep roots that favor "the development of sulfate-reducing bacteria and the production of a fibrous peat rich in pyrites" (Bertrand, 1991, p. 61). Farmers all over the coastal area of the country periodically allow brackish water to enter during the late dry season when high spring tides occur to increase soil fertility and reduce iron and aluminum toxicity. However, the recent variability in the start of the rainy season has been triggering the abandonment of this practice.

Farmers of certain ethnic groups (Balanta, Felupe/Baiote, Manjaco and Pepel), renowned as specialists in MSRP, employ specific techniques for rice cultivation in fields known as *Bolanhas salgadas* (swamp saline rice fields in Kriol). After slashing mangrove tracks, farmers construct primary dikes to prevent brackish water intrusion, and burn the remaining stumps and extract them to clear the fields once the trees perish. Subsequently, they partition the area with secondary dikes (bunds) to create plots for freshwater storage (Temudo, 2011). After the initial rainfall gathers sufficient freshwater to achieve the necessary soil plasticity for plowing (Garbanzo et al. 2024b), farmers with the typical wooden plow tipped with an iron edge called "radi" in Kriol, penetrate the soil at 20–40 cm, leaving the deeper soil undisturbed. Farmers incorporate the rice stubs from the previous year along with green vegetation, which serve as a green manure base for the new ridges.

Smallholder farmer's techniques for freshwater harvest and soil management can alter pedological characteristics. Dikes and furrow-ridge systems are recognized for their effectiveness in water conservation, reducing soil compaction, and soil salinity in fields that depend solely on rainfall (Sylla et al. 1995; Oosterbaan, 1982). Water is then distributed among plots and drained to the river/sea branch by using tubes [palm trunks, *Polyvinyl Chloride* (PVC) tubes] and/or openings in the main dike (only in Oio, Centre) and the bunds. Nevertheless, water storage limitations and soil physicochemical changes, significantly influence farmers' decisions regarding the cultivation or abandonment of some plots. Additionally, unsuitable agronomic practices alter soil physicochemical properties, creating significant challenges in maintaining minimum yield levels, thus often leading to food scarcity and long hunger periods for farmers' families.

Paddies in MSRP are categorized into distinct soil profiles according to tidal influence. Tidal mangrove (TM) soils developed near mangrove forests and are characterized by high reduction and oxidation dynamics, attributed to the tides' influence and groundwater movement. In contrast, associated mangrove (AM) soils exhibit pedofeatures as a result of oxidation due to reduced tidal influence. Smallholder farmers manage TM and AM plots differently, recognizing the differences in soil and yields. Despite the importance of MSR cultivation in West Africa, comprehensive information is often lacking due to limited pedological studies considering soil profile development and differentiation (D'Amico et al., 2023; Andreetta et al., 2016; Teixeira, 1962).

Soil characterization plays a central role in understanding fertility dynamics, evaluating land suitability for diverse crops, and implementing effective soil management practices (Syers and Rimmer, 1994) In the MSRP system, soils tend to be slightly to highly acidic due to the influence of brackish water and sulfate oxidation, leading to the formation of Acid Sulphate Soils (ASS) after polderization. Extensive areas of sulfidic clays are reported in various West African regions, notably in the Niger Delta, the Gambia, and the Guinea coastal strip (Dent and Pons, 1995).

Guinea Bissaús diverse soils result from its topography, ancient geomorphology, and active tropical weathering processes. Most upland soils are Ferralsols according to the World Reference Base (WRB; IUSS Working Group, 2022) or Oxisols according to Soil Taxonomy (1999), characterized by highly sandy textures and low organic matter content, except in densely vegetated areas (secondary forests or cashew orchards). Intense weathering leads to nutrient leaching and iron and aluminum oxides accumulations, which contribute to iron (Fe) and aluminum(Al) toxicity, as described by Teixeira (1962). In the Cacheu northern coastal region, Teixeira (1962) described Regosols (corresponding to Arenosols in WRB), characterized as sandy mineral deep soils lucking distinct horizons. Furthermore, he estimated that approximately 20 % of the total country is covered by Hydromorphic soils, classified into "continental hydromorphic" and "hydromorphic marine alluvium", the latter influenced by tides, consist of low flat plains that remain submerged for extended periods (Teixeira, 1962). According to WRB classification, Gleysols and Humic Gleysols are among the marine hydromorphic soils commonly found in MSR paddies. These halo-hydromorphic soils directly impacted by tides exhibit high salinity concentrations (Baggie et al., 2018; Dent and Pons, 1995).

Land suitability assessment can be described as an evaluation of the suitability of land or soil for specific crop production purposes (Bock et al., 2018). It encompasses various criteria, including climatic conditions, soil properties, and land topography, and aims to identify suitable land use options and determine the most appropriate management strategies for rice cultivation (Marzouk et al., 2023; Massawe et al., 2017). FAO's land evaluation guidelines provide precise guidance worldwide on the land evaluation procedure and criteria used (FAO, 2007). Considering the absence of this information about MSRP fields in Guinea Bissau, this research is going to adopt a comprehensive approach to understanding the physicochemical characteristics of MSRP fields, associating it with soil suitability assessments (SSA).

Thus, the objective of this study was to characterize and describe the key soil properties present in two types of MSR fields to identify the main limiting factors to rice production. Simultaneously, by recognizing the limitations farmers currently face, we identify the strategies they use to overcome these obstacles, including their existing practices, solutions, and knowledge. This study provides a foundation for future research aimed at addressing agricultural challenges such as soil salinization and acidification to develop targeted, practical solutions and recommendations rooted in nature-based strategies. These approaches are not only applicable to Guinea-Bissau but also relevant to broader areas of West Africa where similar agro-ecosystem are used and were salt-affected soils comprise at least 10 per cent of the world's arable land (FAO, 2024).

2. Materials and methods

2.1. Study area

The soil characterization in this study was carried out during the dry season of 2022–2023 in the coastal areas of Guinea-Bissau (Fig. 1). Soil profiles were opened between February and May to avoid waterlogging issues in the plots used for rice production. Two soil profiles were excavated and characterized in each of the four selected villages, representing the MSRP areas of the southern (Cafine [CA]), central (Enchugal [EN] and Malafu [MA]), and northern (Elalab [EL]) regions of the country. The selection criteria for sites within the villages included: a) representation of primary agroecology in the paddies, encompassing both low-lying fields (Tidal Mangrove [TM]) and mid- to high-lying fields (Associated Mangrove [AM]) across the catena; b) the selection of adequately homogeneous and representative fields for each agroecology was determined based on the profiling display observed along transects conducted using an auger. Therefore, the selected areas were geographically located as shown in Table 1. See Fig. 2 (A-D) showing the surrounding landscape for TM and AM profiles during the production season in – August, and during the dry season in February (when profiles were escavated).

Guinea-Bissau has a tropical monsoon climate by Köppen-Geiger classification (Beck et al., 2018) and exhibits diverse agro-climatic conditions from north to south and from the coast toward the interior. The southern region of the country records the highest rainfalls between June and October, totaling 2513 and 2115 mm respectively for 2021 and 2022, with August being the wettest month (Fig. 3A). The temperatures remained elevated throughout the year, reaching a maximum of 39.3 °C in March and a minimum of 17.5 °C in December. In the Oio region, a total rainfall of 1519 and 1500 mm was recorded in 2021, while for 2022 registered 1360 and 1512 mm (respectively for Malafu and Enchugal). August received 600 and 745 mm for 2021, and 595 and 537 mm for 2022(respectively for Malafu and Enchugal). Temperatures in Malafu varied from a maximum of 43.1 °C in May to a minimum of 12.2 °C in December, while in Enchugal reaches a maximum of 42.1 °C in May and a minimum of 13.5 °C in December, showing a big micro-climatic variability within the Oio region. The Northern region typically experiences less rainfall compared to other regions. However, 2022 deviated from this trend, with a total precipitation of 1690 mm recorded in Elalab, surpassing that of the Oio region. Temperatures in the Northern region ranged from a maximum of 37 °C to a minimum of 16.6 °C in January.

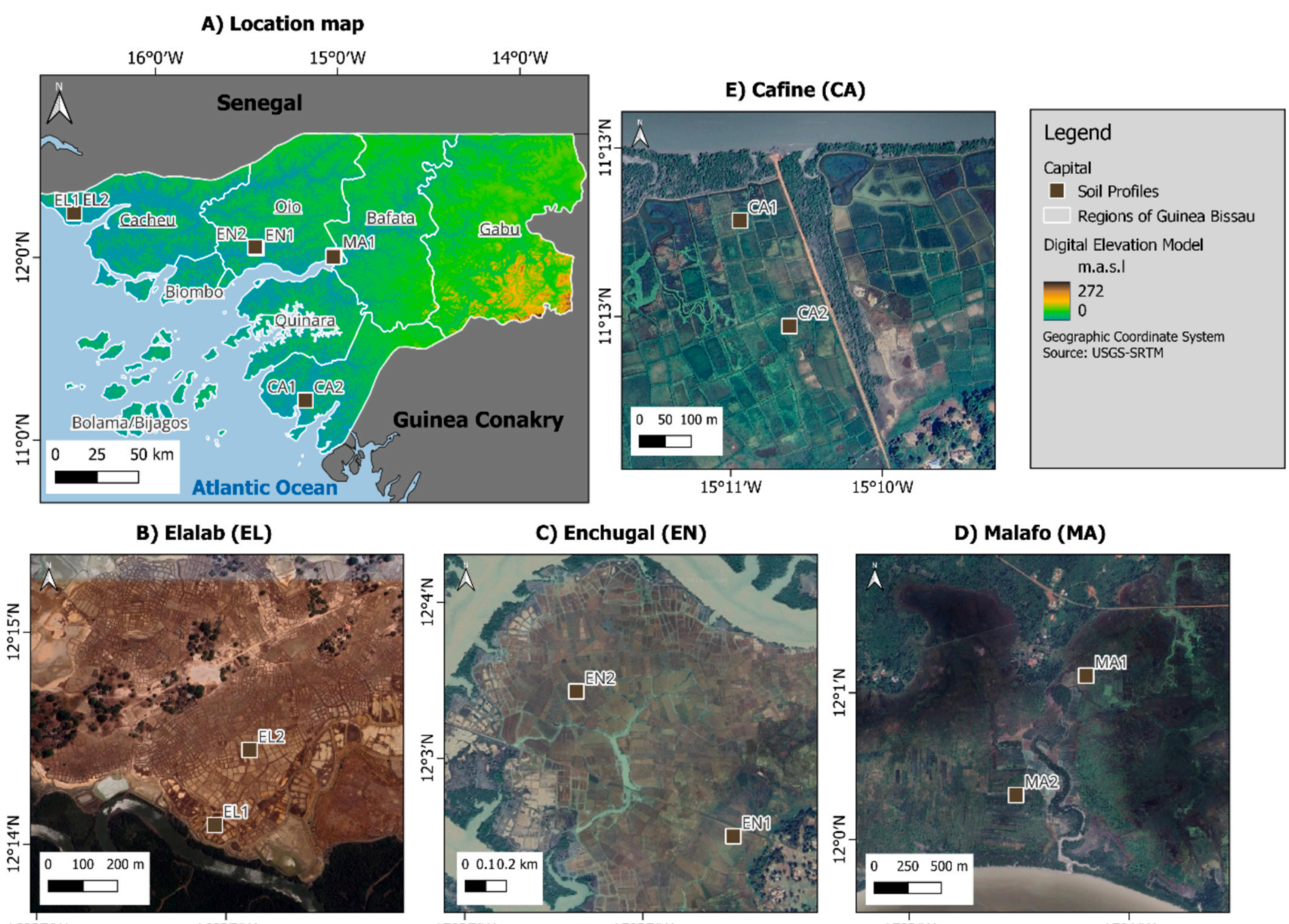

Fig. 1. Location of the eight soil profiles in mangrove swamp rice production areas (A) across the northern (B), central (C and D), and southern (E) regions of Guinea-Bissau.

Table 1
Identification and coordinates of eight soil profiles characterized in mangrove swamp rice production areas spanning the North, Centre and South of Guinea-Bissau.

Region	Villages	Soil profile ID	Map labels (Fig. 1)	W	N	Holdridge's life zones system+
South **Tombali**	Cafine	CA – TM*	CA1	15°10′35.5″	11°13′07.4″	Tropical moist forest
		CA – AM	CA2	15°10′32.4″	11°13′00.6″	
Central Oio	Malafu	MA – TM	MA1	15°01′04.6″	12°0′40.2″	Tropical dry forest
		MA – AM	MA2	15°01′21.8″	12°0′10.9″	
	Enchugal	EN – TM	EN2	15°27′03.6″	12°03′25.2″	Tropical dry forest
		EN – AM	EN1	15°26′38.2″	12°03′01.8″	
North **Cacheu**	Elalab	EL – TM	EL1	16°26′43.1″	12°14′31.6″	Tropical dry forest
		EL – AM	EL2	16°26′39.8″	12°14′38.7″	

*TM = Tidal Mangrove, AM = Associated Mangrove. Holdrigés life zones system as defined by Harris (1973).

Fig. 2. Cafine village profiles: A. CA-TM location during the production season August 2022; B. CA-TM location during the dry season February 2023; C. CA-AM during production season August 2022; CA-AM during dry season February 2023; E. Malafu village MA–Viv 1 during the nursery plowing July 2023; F. Uncur village UN–Viv 1 during the nursery preparation July 2023.

2.2. Soil sampling and laboratory methods

In the mentioned locations (Fig. 1, four villages), the soil profile sampling and description were systematically conducted following the methodology described in the Field Book for Describing and Sampling Soils (Schoeneberger et al. 2012). The profiles were excavated to a maximum depth of 2 m (beyond this depth, waterlogging prevented further excavation). For each horizon, three replicates were sampled for physical analysis (undisturbed cylinders), along with two additional samples (0.5 kg each) for chemical, texture, and mineralogical analyses. Nurseries in the upland soils surrounding the households are typical of Oio region (see Fig. 2 E-F), while in the south and north of the country, farmers establish most of their nurseries directly in the rice fields (Bolanhas in kriol). Thus, in the Oio villages, many nursery soils were identified as problematic (farmers reported poor seedlings growth), and issues such as yellowing and bronzing of rice leaves were observed. Therefore, after identifying some of the ̈problematic ̈ nurseries, composite topsoil samples (five single samples in plots of approximately 100 m^2) from the first 20 cm (the rice root zone) were collected and analyzed from six seedbed soils in the Oio region, including villages Malafu, Enchugal, Uncur, and Blafchur (Table 2, Fig. 3B, 3C).The soil samples were meticulously packaged, labeled, and transported to the soil and water laboratory in Bissau, where they underwent drying, grinding, and preparation for subsequent shipment to other laboratories. Additionally, soil physical analyses were conducted at Bissau's laboratory, recently rehabilitated by two of the authors.

Particle size distribution analyses were conducted using the Bouyoucos methodology, following the validated method by the Soil Survey Staff for the implantation of Hydrometers (Soil Survey Staff, 2014; Day 1965; Bouyoucos, 1936). Furthermore, bulk density was determined using cylinders with known volumes, replicated three times in each horizon. Particle density was assessed using a water displacement method, utilizing volumetrically calibrated flasks and soil–water masses calibrated for temperature. Both bulk and particle densities were evaluated following methodologies specific to tropical soils (Forsythe, 1985) in Bissau's laboratory. Additionally, to facilitate the analysis of soil–water retention, undisturbed samples were carefully sealed and transported to the soil laboratory at the School of Agriculture (ISA) of the University of Lisbon. Upon arrival, these samples underwent rehydration until soil saturation and were subsequently placed on pressure plates to assess gravimetric moisture levels at pressures of 0.33 and 15 bar (Klute, 1986; Forsythe, 1985; Richards and Fireman, 1943). Thus, volumetric moisture content was then estimated utilizing the respective cylinder volumes, while plant available water was determined through the subtraction of moisture levels between the two retention points (field capacity and permanent wilting point).

Chemical soil analyses were conducted following the methodologies outlined by the Soil Survey Staff for this soil characterization (Soil Survey Staff, 2014). To achieve this, soil extractions were performed using ammonium acetate (1 N, pH 7) for Na, Ca, Mg, K and cation exchange capacity (CEC). Also, ammonium oxalate (0.2 M, pH 3.5) was used for Al and Fe extractions. Subsequently, the extracted solution underwent analysis using inductively coupled plasma mass spectrometry to quantify the concentration of elements in each soil sample. In addition, the pH-water (1:1 water:soil), pH-KCl (1 N), Electric Conductivity (EC1:2.5) and the soil exchangeable acidity (KCl 1 M) were

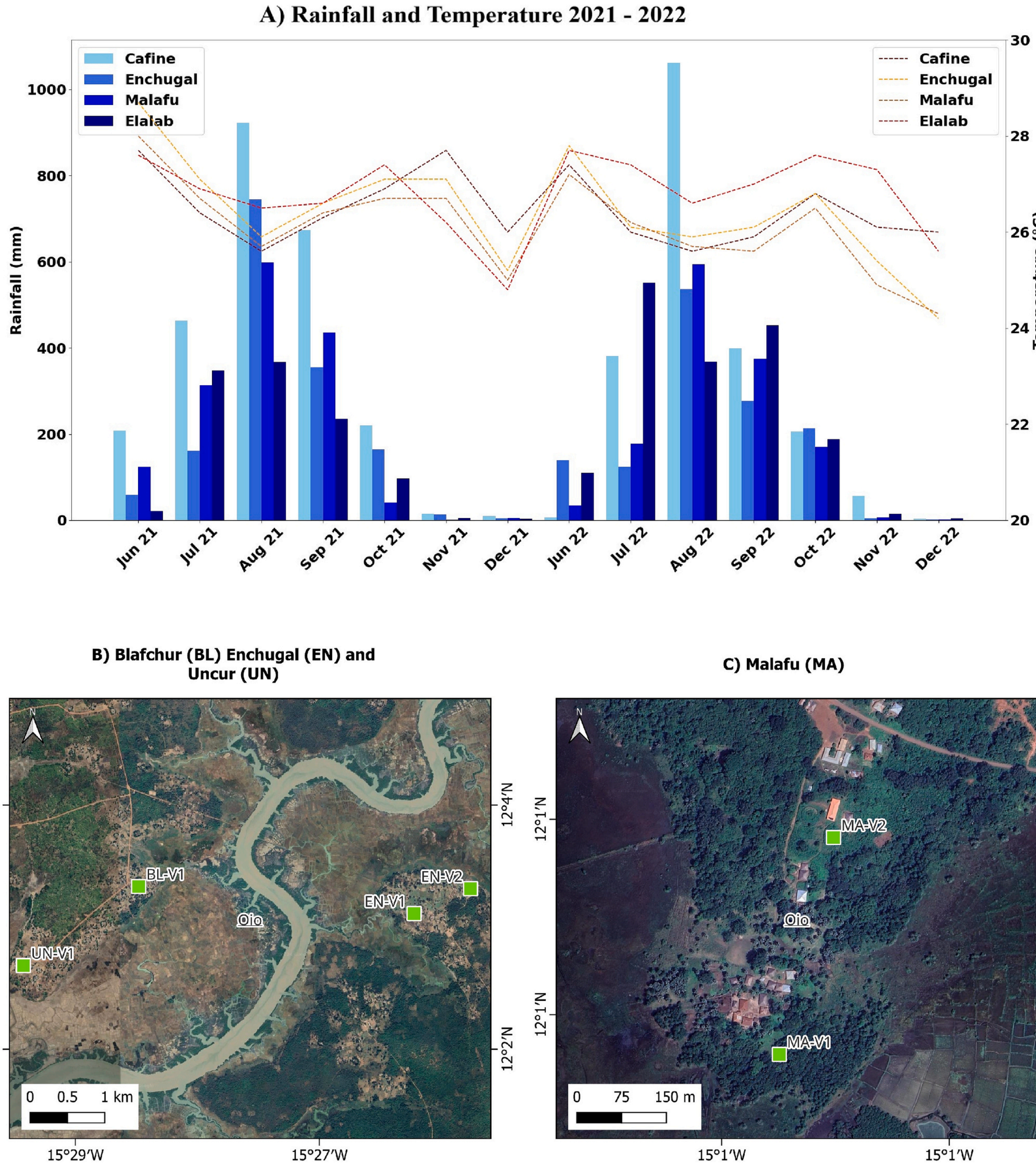

Fig. 3. Monthly total rainfall and mean temperatures from the four meteorological stations Cafine, Entchugal, Malafu, and Elalab for 2021 and 2022 (A); Nurseries and topsoil sample for Enchugal, Uncur and Blafchur (B) and Malafu (C). A-.
Source: Malmon project meteorological stations network

determined. Subsequently, total nitrogen (TN) and total carbon (TC) contents were determined using an auto analyzer via dry combustion (Horneck and Miller, 1998). Finally, available phosphate was extracted with the extracted solution Mehlich 3 (HOAc 0.2 M, NH_4NO_3 0.25 M, NH_4F 0.015 M, NHO_3 0.013 M, EDTA 0.001 M, pH 2.5) (Mehlich, 1984). All chemical analyses were conducted at the Soil and Foliar Laboratory of the Agronomic Research Center.

Total mineralogy and the saturated clay fraction (<2mm) were separated by sedimentation and flocculation with $MgCl_2$, washed out from Cl^-, and then analyzed by X-ray diffractometer system XPERT-PRO, in a powdered soil samples instrument, using CuKa radiation (k = 1.5406 A^0). The qualitative and semi-quantitative mineral abundance was made with the XPowder software (Martin, 2004).

2.3. Soil classification and soil suitability assessments (SSA)

The profileś soil classification was conducted according to the “reference soil groups” and “qualifiers” outlined by the IUSS Working Group WRB (2022). For field description of morphological properties, we used the Soil Survey Staff 2012 (Schoenebergeret al., 2012). Soil

Table 2
Identification and coordinates of six nursery topsoil in the Oio region, central of Guinea-Bissau.

Region	Villages	Nursery Sample ID	Map labels (Fig. 2)	W	N	Holdridge's life zones system+
Central	Malafu	MA–Viv 1	MA-V1	15°01′16″	12°00′41″	Tropical dry forest
	Enchugal					
Oio		MA–Viv 2	MA-V2	15°01′13″	12°00′53″	
	Enchugal	EN–Viv 1	EN-V1	15°26′18″	12°02′48″	
		EN–Viv 2	EN-V2	15°25′53″	12°02′59″	Tropical dry forest
	Uncur	UN–Viv 1	UN-V1	15°29′11″	12°02′25″	
	Blafchur	BL–Viv 1	BL-V1	15°28′20″	12°03′00″	

suitability assessments (SSA) for the studied profiles (eight) and nursery top-soil samples (six) were performed using the simple limitation methods as delineated by (Sys et al., 1991), utilizing suitability classes recommended by the FAO guideline (1985) and adapted for the rice crop requirement by Sys et al., (1993) (see Table 3). The suitability classes were adapted including S1 for "*high suitability*", S2 for "*moderate suitability*", S3 for "*marginal suitability*", and N being the "*not suitable*" class. The SSA matrix considered 19 soil parameters evaluated across four primary qualifiers: climatic conditions (c), topography encompassing drainage and flooding conditions (t), soil physical properties (p), and soil chemical properties indicative of fertility status (f) (Table 3). Finally, we categorized soils into three groups of increasing susceptibility: A- when limited classes (S3/N) $\leq$ 3, B- when (S3/N) = 4 to 6, and C- when (S3/N) $\geq$ 7. If only one property is classified as N, the group is designed as not susceptible for correction. Rice production qualifiers and growing factors were not taken into account in this stage of the analyses.

3. Results

3.1. Soil morphological description

In general, the profiles of Cafine (south) and Malafu and Enchugal (centre) exhibit considerable similarity in their morphological characteristics (Fig. 4). These soils typically display an angular (abk) or subangular (sbk) blocky structure, transitioning at times to more massive (m) formations in deeper horizons (CA TM & CA AM; Table 4). In the case of the Enchugal profiles, a moderately granular (gr) topsoil structure is observed, accompanied by well-developed slicken sides starting in the B horizons (EN AM). Soil color tends to be predominantly reddish yellow, ranging from 10YR to 2.5 YR, occasionally shifting to yellowish 2.5Y to 5Y hues. Towards deeper horizons, indications of gleyic properties manifest in dark grey colors 1 4/N. These profiles demonstrate a predominantly moderately sticky (ss) to very sticky (vs) consistency, coupled with high (p) to very high plasticity (vp). Notably, yellow-orange to reddish mottles, largely comprising small to medium-sized Fe hydroxides, are prevalent in the upper horizons of Bw (Fig. 4).

In contrast, profiles from Elalab feature an angular blocky (abk) structure in the topsoil horizons but transition to a structureless single grain (sg) configuration in the subsoil horizons (Bw and C) owing to their sandy texture (Table 5). Soil color primarily consists of reddish yellow 10YR for the TM profile, while the AM profile displays an alternation between reddish yellow 10YR and yellow 2.5Y to 5Y. These profiles predominantly exhibit non-sticky (so) to slightly sticky (ss) consistency and lack plasticity (po). Furthermore, they do not exhibit gleyic color patterns or the formation of mottles or spots.

3.2. Soil physical and chemical characterization

Topsoil in CA, MA, and EN exhibit high clay content, which decreases towards the subsoil, resulting in silty loam and sandy loam textures (Table 5). The high clay content in the topsoil is likely attributed to the deposition of fine materials carried by runoff from erosive slopes, while increased sand content in deeper layers may result from heavy particle deposition. Particle size analysis, including

Table 3
Soil suitability assessment (SSA) climatic, topography, physical and chemical properties, ranges for S1, S2, S3 and N classes.

Environmental Factors	Nr.	Environmental and Soil Parameters	S1 (85–100)	S2 (60–85)	S3 (40–60)	N (0–40)
1. Climate (c)	1	Annual rainfall (mm)	>1500	1500–1000	1000–800	<800
	2	Nr. Dry Months	0–3	4–5	6–7	>7
	3	Mean annual temp. (°C)	35–22	22–20	20–16	<16; >35
	4	Relative humidity (%)	>70	70–65	65–60	<60
2.Topography (t)	5	Slope gradient (%)	<4	4–8	9–16	>16
	6	Drainage	v.p.d	p.d	g.d	v.g.d
	7	Flooding	F0	F1	F2	F3
3. Soil physical properties (p)	8	Soil depth (cm)	>75	60–75	50–60	<50
	9	Texture	C, SiCL	SiC, CL	SiL, SC	L, SCL;SL,LS, S
	10	Gravel (%)	<5	5–15	16–30	>30
4. Soil chemical properties (f)	11	pH	7.8–6.0	5.9–5.0, 8.4–7.8	4.9–4.0	<4.0; >8.4
	12	TC (%)	>2	2–1.5	1.4–0.8	<0.8
	13	TN (%)	>0.30	0.30–0.20	0.19–0.10	<0.10
	14	Av. P (mg kg^{-1})	>6.0	6.0–4.1	4.0–2.0	<2.0
	15	Exchange K (cmol kg^{-1})	>0.40	0.39–0.20	0.19–0.10	<0.10
	16	CEC (cmol kg^{-1})	>20	20–15	14–8	<8
	17	BS (%)	100–75	74–50	49–30	<30
	18	EC (dS m^{-1})	0–2.0	2.1–4.0	4.1–6.0	>6.0
	19	ESP (%)	<15	15–20	21–30	>30

Notes: **drainage** – v.p.d (very poor drainage), p.d (poor drainage), g.d (good drainage), v.g.d (very good drainage); **flooding** – F0 (no flooding limitation- the ridges are higher than the highest water level), F1 (slight limitation –occasional high floods affecting no longer than 1–2 months), F2 (Moderate Limitation –5 out of 10 years the soil is flooded 2–3 months), F3 (Severe limitation – ridges are flooded 20–30 cm for 2—4 months every year), F4 (very severe – ridges are flooded > 30 cm for > 4 months every year); **Surface texture –** C (clay), SiCL (silty clay loam), CL(clay loam), SiC (silty clay), SiL (silty loam), SC (sandy clay), L (loam), SCL (sandy clay loam), SL (sandy loam), LS (loamy sand), S (sand); TC (Total Carbon), TN (Total Nitrogen), Av. P (available phosphorus), CEC (Cation Exchange Capacity), BS (Bases Saturation), EC (Electrical Conductivity), ESP (Exchangeable Sodium Percentage). All selected parameters are considered for the surface 0 to 20 cm soil layer.

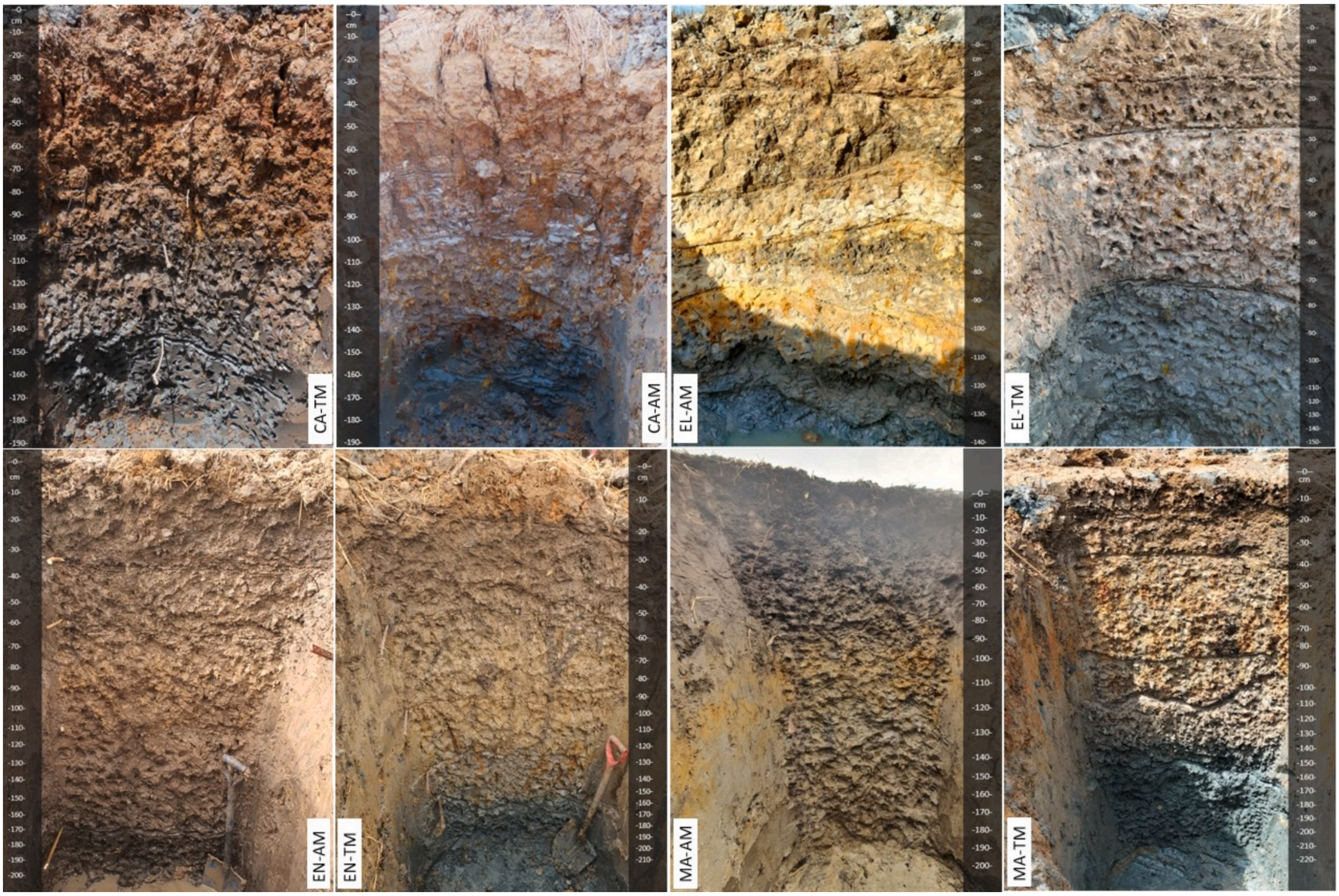

Fig. 4. Morphology and profile depth of eight profiles sampled and studied in three coastal regions in Guinea-Bissau: CA TM & CA AM (southern, Cafine), EN TM & EN AM (central, Enchugal), MA TM & MA AM (central, Malafu), and EL TM & EL AM (northen, Elalab).

measurements of bulk density, porosity, and particle density, are fundamental soil properties that offer insights into soil compaction and root penetration. These parameters reveal minimal differences, with a slight increase observed in the upper Bw horizons followed by a subsequent decrease at greater depths. Surface soils within the mentioned profiles exhibit bulk densities ranging from 1.1 to 1.4 g cm^{-3}, indicating the absence of restrictive compaction in the topsoil. Subsoils generally show values below 1 g cm^{-3} and porosity 62 to 80 %, except for the MA AM profile, where values resemble those of the topsoil.

Both EL profiles predominantly display sandy texture with consistent particle size distribution throughout the profiles. However, bulk density exceeds critical limits (> 1.6 g cm^{-3}) for sandy soils, particularly in the deeper horizons of profile EL AM, likely due to very low porosity, high sand content, and minimal organic matter, as suggested by Pravin et al. (2013).

Electrical Conductivity (EC) serves as an indicator of soil salinity and exhibits a consistent trend across all examined profiles, displaying a notable increase towards the subsoil (Table 6). Profiles located proximate to river branches heavily influenced by tidal fluctuations (TM profiles) manifest the most pronounced salinity issues. Subsoils in CA TM, MA TM, and EN TM profiles exhibit elevated EC values, peaking 57 dS m^{-1}, 44 dS m^{-1}, and 47 dS m^{-1}, respectively. Additionally, CA AM and EN AM show saline sub-layers with EC levels reaching 37 dS m^{-1} and 28 dS m^{-1} respectively. EL TM exhibits significant salt accumulation in the Ap horizon, with concentration reaching 30 dS m^{-1}, extending to the deeper layers. Remarkably, MA AM remains unaffected by salinity limitations.

Soil pH plays a critical role in assessing soil suitability for rice cultivation. Profiles from Cafine (both TM and AM) demonstrate acidity throughout the profile, except for Bg in CA AM (Table 6). Similarly, EL TM, MA TM, and EN AM profiles exhibit high acidity levels ($pH_{H2O} < 4$), with markedly elevated exchangeable acidity observed in deeper horizons, reaching 16.8 cmol(+) kg^{-1} and 25.6 cmol(+) kg^{-1} for MA TM Bg2 and EN AM Bg, respectively, while pH_{H2O} was below 3. Across all profiles, the pH (H_2O) exceeds that of pH (KCl) and notably falls below the observed field pH, a phenomenon attributed to pyrite oxidation resulting in sulfuric acid formation. Additional water samples collected from acidic soil creeks reveal even lower acidity levels, occasionally registering pH values below 3.

The total carbon (TC %) concentrations are also influenced by a displacement along the profile where, in all profiles, the surface layer Ap has high TC % that decrease in the first B horizons but then increase again in the deep horizons (Table 6). Elalab profiles are also the poorest in carbon concentrations, on average, while in the MA AM profile, the Ap horizon has a very high concentration compared to the last Bg (2.6 % versus 0.18 %). C accumulations in the depths of the EN AM reach remarkably high values, approaching 4.3 %. The elevated porosity, diminished bulk density, and substantial carbon deposits in the lower layers stem from the presence of deep-rooted ancient mangroves (Fig. 5).

The total nitrogen (TN %) content varies significantly across the profiles, with CF TM exhibiting consistently high concentrations (average 0.18 %), followed by CA AM with medium concentrations (0.12 %). EN TM, EN AM, MA TM, and MA AM display slightly lower but still moderate levels of nitrogen (0.10 %). Conversely, EL TM and EL AM profiles exhibit notably lower nitrogen concentrations, with values of 0.07 % and 0.05 %, respectively.

Regarding the available P (Av. P), there is a clear increase trend

Table 4
Soil profile morphological feature.

Profile	Horizon	Depth (cm)	Color (dry)	Mottles Color (dry)	Structure[a]	Consistence[b]	Boundary[c]
CA TM	Ap	0 – 39	10YR 7/8		Pr/ co/ 3	ss/ ps/ mh	WD
	AB	39 – 63	10YR 6/2		Pr/ co/ 3	ss/ ps/ vh	WD
	Bg1	63 – 85	7.5YR 6/0	7.5YR 6/2	Abk/ m/ 1	s/ p/ ha	SG
	Bgj	85 – 134	2.5YR 5/0	5Y 8/4	Abk/ m/ 1	s/ p/ ha	SG
	Bg2	134—180+	2.5Y 5/0	5Y 8/3	m/ 0	s/ p/ fr	SC
CA AM	Ap	0 – 30	5YR 5/8	10YR 6/3	Abk/ co, vc/ 3	s/ vp/ h	WG
	AB	30 – 48	10YR 6/2	7.5YR 5/6	Abk/ co, m / 3	s/ vp/ ha	WG
	Bi	48 – 74	5Y 6/1	2.5Y 5/6	Abk/ m/ 2, 3	vs/ vp/ mh	SG
	Bgj1	74 – 118	2.5Y 6/4	5Y 5/1	m/ 0	s/ vp/ mh	SC
	Bgj2	118 – 153	7.5YR 6/0	2.5YR 3/6	m/ 0	vs/ vp/ fr	SC
	Bg	153 – 190+	10YR 6/1		m/ 0	vs/ vp/ fr	SC
EL TM	Ap	0 – 15	10 YR 5/8		Abk/ vf, f, m/ 1	ss/ sp/ fi	SA
	Bw	15 – 28	10 YR 7/3		Abk/ m,co/2	ss/ sp/ fi	SC
	C	28 – 73	10 YR 7/1		Sg/ Vf, f/ 0	so/ so/lo	SG
	Cg	73 – 140+	2.5 Y 6/2		Sg/ Vf, f/ 0	so/ so/ lo	SG
EL AM	Ap	0 – 13	10YR 6/4		Abk/ m,co/2	s/ p/ efi	WG
	Bw	13 – 40	10YR 5/6		Abk/ m,co/2–3	s/ p/ efi	WG
	C1	40 – 53	2.5Y 6/2		Sg/ vf, f/ 0	so/ po/lo	SC
	C2	55 – 70	5Y 7/2		Sg/ vf, f/ 0	so/ po/lo	SG
	C3	70 – 80	10YR 7/6		Sg/ vf, f/ 0	so/ po/ lo	SG
	Cg1	80 – 100	5Y 7/2		Sg/ vf / 0	so/ po/ lo	SG
	Cg2	100 – 165+	5Y 7/1		Sg/ f/ 0	so/ po/ lo	SG
MA TM	Ap	0 – 20	10YR 3/3		Abk / m / 2 *m*	s / p / fi	SA
	AB	20 – 35	10YR 4/2		Abk / m –f / 2 *m*	s / p / vfi	SA
	Bw	35 – 85	10YR 5.5/2	5YR 5.5/8	Abk / m –f / 2mf	s / p / fi → vfi	WG
	Bj	85 – 110	10YR 6/1	5YR 6/8	Abk / m –f / 2 *m*	vs/ ps /fi	WG
	Bg1	110 –150	2.5Y 5/2	2.5Y 6/6	Abk / m –f / 2->1*m*	vs / vp / fi	WG
	Bg2	150 – 220	1 4.5/N		Abk / m –f / 2->1*m*	vs / vp / vfr	SA
MA AM	Ap	0 – 45	10YR 3/1		Abk / f → vf / 3	s / vp / eh	WA
	Bi1	45 – 80	10YR 4/2		Sbk / m → f/ 1	ss / vp / fr	WA
	Bi2	80 – 115	10YR 6/2.5	10YR 7/8	Sbk / m → f / 1	s / vp / fr	WA
	Bi3	115 –148	10YR 6/1		Sbk / m → f / 2	s / p / fi	WA
	Bg	148 – 200+	2.5Y 6/2	10YR 6/7	Abk / m → f / 1	s / p / fr	WA
EN TM	Ap	0 – 20	10YR 3.5/1		Gr / co, m → f / 2	s / p / eh	SV
	Bw1	20 – 54	10YR 4/2		Sbk / m → f → vf / 1	ss / p /fi	SV
	Bw2	54 – 100	10YR 6/2		Sbk / m → f → vf / 1	s / ps /fi	SV
	Bj	100 – 138	10YR 6.5/2	2.5Y 8/7	Sbk / m → f / 1	vs / ps /fr	SV
	Bg1	138 – 180	2.5Y 5/1	7.5YR 6/6	Sbk / m → f / 2	s / ps /fr	SV
	Bg2	180 – 210+	1 4/N		Sbk / m → f / 2	s / ps /fr	SV
EN AM	Ap	0 – 40	10YR 3/2		Gr/Sbk /co → m /2	s / p / vfi	SV
	Bij1	40 – 65	10YR 5.5/2		Sbk / m → f / 1	s / vp / vfi	SV
	Bij2	65 – 119	10YR 5/4	10YR 7/6	Sbk / m → f / 1	s / p / vfi	SV
	Bi	119 – 172	10YR 5/1		Sbk / m → f / 1	vs / p / fr	SV
	Bg	172 – 200+	2.5Y 4/1	7.5YR 6/8	Sbk / m → f / 1	s/ p / fi	SV

[a] Soil structure, **type**: massive (m); granular (Gr); subangular blocky (Sbk); angular blocky (Abk), single grain (Sg); **size**: very coarse (vc); coarse (c); medium (m); fine (f); very fine (vf); **grade**: strong (1); moderate (2); weak (3) (Schoeneberger et al., 2012). [b]Consistence, **Stickiness and plasticity**: nonsticky (so), sticky (s); slightly sticky (ss); very sticky (vs); nonplastic (po), plastic (p); slightly plastic (ps); very plastic (vp). **Rupture resistance**: loose (lo), soft (s), moderate hard (mh), hard (ha), very hard (vh), extremely hard (eh), firm (f), moderately firm (fi); very firm (vfi), moderately friable (fr), very rigid (efi) (Schoeneberger et al., 2012). [c]Boundaries: smooth (S); wavy (W); clear (C); gradual (G); diffuse (D) (Schoeneberger et al., 2012).

going top-down the subsoils for all profiles (Table 6).

The soil profile analysis of Cafine in CA TM and CA AM, revealed no differences in concentration of Av. P (means respectively 22 and 30 mg/l). In Enchugal profiles, it is evident that the P concentration in EN TM exceeds that of the AM profile by more than double across the entire profile (45 versus 17 mg L^{-1}). MA AM and EL AM exhibit the lowest concentrations, averaging around 6 mg/l. However, there isn't much improvement in concentrations for MA TM, averaging around 18 mg L^{-1}, and EL TM, averaging 8.5 mg L^{-1}.

The cation-exchange capacity (CEC) values are high for most of the profiles with mean values ranging between 22 and 28 cmol (+) kg^{-1} (Table 6). Soil profiles in Elalab showed low CEC in TM and AM (6.4 and 4.3 cmol (+) kg^{-1} respectively), being slightly higher in the first two topsoil horizons (6.4–12.9 cmol (+) kg^{-1}). The loamy, sandy and sandy loamy textures of Elalab soils, perfectly drained, facilitate rapid leaching, resulting in the loss of basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) being in very low disposition along these two profiles. Subsequent mineralogy analysis reveals that these soils predominantly consist of kaolinite, a clay known for its relatively low CEC.

However, high Mg^{2+} ions concentrations are observed in the deeper horizons of CA TM, MA TM and EN TM aligning with very high Na^+ concentrations, saturating completely these horizons. The soil K^+ supply capacity seems to be very low for Elalab profiles (EL TM & EL AM), as well for MA AM profile with K^+ values that do not exceed 1 cmol (+) kg^{-1} along the profile.

3.3. Soil mineralogy and taxonomic classification

3.3.1. Mineralogy

Soil minerals serve as the primary repository for essential plant nutrients, gradually releasing them through biochemical weathering processes and facilitating nutrient retention via cation and anion exchange mechanisms. Clay mineralogy analysis of the profiles unveiled a predominant composition primarily comprising quartz and kaolinite minerals, with few variations observed along the profiles. EL AM and EL TM profiles exhibit almost exclusive quartz composition (96 %) and trace in kaolinite and smectite all along the profile, indicative of poor clay 2:1 mineral content. Both CA TM and CA AM display a higher quartz composition (≈83 %), with both profiles containing low amounts of smectite (2 to 3.5 %) and jarosite formations starting in the upper AB

Table 5
Soil physical and water retention properties.

Profile	Horizon	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density (g/cm^3)	Total Porosity (%)	Field capacity (%)	Permanent wilting (%)	Available water (%)
CA TM	Ap	19	39	42	Clay	1.09	0.57	32.7	21.4	11.3
	AB	36	24	40	Clay	1.16	0.56	25.4	21.0	4.4
	Bg1	48	28	24	Loam	0.87	0.64	42.8	31.5	11.3
	Bgj	57	30	13	Sandy Loam	0.69	0.73	51.1	33.0	18.1
	Bg2	45	48	7	Loam	0.59	0.77	58.4	40.0	18.4
CA AM	Ap	17	38	45	Clay	1.17	0.54	37.1	19.0	18.1
	AB	12	31	57	Clay	1.15	0.56	45.4	30.1	15.3
	Bi	31	32	37	Clay Loam	0.98	0.62	47.6	21.5	26.1
	Bgj1	40	35	25	Loam	0.62	0.76	57.4	27.2	30.2
	Bgj2	52	43	5	Sandy Loam	0.57	0.79	68.1	37.0	31.1
	Bg	44	50	6	Silt Loam	0.74	0.73	54.4	22.3	32.1
EL TM	Ap	54	37	9	Sandy Loam	1.47	0.45	32.6	20.0	12.6
	Bw	46	32	22	Loam	1.49	0.44	41.6	25.5	16.1
	C	88	7	5	Sand	1.47	0.45	32.3	14.4	17.9
	Cg	90	6	4	Sand	1.40	0.46	28.7	15.7	13.0
EL AM	Ap	68	13	19	Sandy Loam	1.53	0.42	21.1	10.0	11.0
	Bw	44	21	35	Clay Loam	1.65	0.38	34.1	13.1	21.0
	C1	94	2	4	Sand	1.52	0.42	13.6	6.3	7.3
	C2	84	7	9	Loamy Sand	1.51	0.42	9.4	6.2	3.2
	C3	94	2	4	Sand	1.60	0.39	7.8	7.6	0.2
	Cg1	90	4	6	Sand	1.59	0.40	18.9	7.6	1.13
	Cg2	92	4	4	Sand	1.73	0.35	30.0	13.0	17.0
MA TM	Ap	5	28	67	Clay	1.2	0.52	38.9	31.7	7.2
	AB	5	36	59	Clay	1.25	0.49	39.0	32.5	6.4
	Bw	22	34	44	Clay	1.06	0.57	58.4	49.3	9.0
	Bj	36	37	27	Clay Loam	0.86	0.65	73.0	57.0	16.0
	Bg1	44	44	12	Loam	0.83	0.66	81.0	55.9	25.4
	Bg2	44	51	5	Sandy Loam	0.96	NA	NA	NA	NA
MA AM	Ap	18	32	50	Clay	1.17	0.52	34.1	23.0	11.2
	Bi1	5	28	67	Clay	1.39	0.39	35.9	24.9	11.0
	Bi2	3	28	69	Clay	1.33	0.46	41.9	29.0	12.9
	Bi3	3	32	65	Clay	1.20	0.51	48.2	31.9	16.3
	Bg	7	24	69	Clay	1.15	0.53	48.5	31.8	16.7
EN TM	Ap	11	31	58	Clay	1.17	NA	NA	NA	NA
	Bw1	9	41	50	Clay Loam	1.36	NA	NA	NA	NA
	Bw2	30	34	36	Silty Clay	1.03	NA	NA	NA	NA
	Bj	55	25	20	Sandy Clay loam	0.85	NA	NA	NA	NA
	Bg1	47	46	7	Loam	0.80	NA	NA	NA	NA
	Bg2	53	40	7	Sandy Loam	0.72	NA	NA	NA	NA
EN AM	Ap	9	37	54	Clay	1.34	NA	NA	NA	NA
	Bij1	12	36	52	Clay	1.29	NA	NA	NA	NA
	Bij2	35	25	40	Clay	1.07	NA	NA	NA	NA
	Bi	38	28	34	Clay Loam	0.82	NA	NA	NA	NA
	Bg	64	18	18	Clay Loam	0.65	NA	NA	NA	NA

Note: Not Analyzed (NA) properties due to equipment default.

horizons for CA TM and accumulating in the Bgj1 and Bgj2 horizons for CA AM (Fig. 6). Similarly, Enchugal profiles, also dominant by a quartz composition (around 70 %), showcase smectite (3,5 to 5 %), ilite (5 to 3,5%) and jarosite formations in the subsurface horizons, originating from Bj in EN TM and Bi2 in EN AM with higher presence (7,5%). In the case of Malafu, sporadic occurrences of jarosite formations are observed, primarily in the Bj and Bg1 horizons of MA TM. Jarosite, an iron and sulfur-bearing mineral, serves as a strong indicator of acid sulfate soil oxidation and is typically formed in environments with excessively acidic soil conditions (pH less than 4, consistent with the very low pH values in Table 4). Additionally, halite compounds were identified in the profiles of EN TM, EN AM, and MA TM.

Furthermore, mineralogy for nurseries' topsoil showed a composition dominated by quartz ranging from 90 % for MA-Viv1 to a maximum of 99 % for BL-Viv1 (Blafchur), followed by kaolinite which ranged from 5 % for MA-Viv1 to 0.8 % for BL-Viv1 (Blafchur), while smectite and elite show very low (does not exceed 3 % in MA-Viv1) or even in trace quantities for BL-Viv1, indicating a very poor clay 2:1 content.

3.3.2. Soil profiles classification

Based on the field and laboratory analyses the classification of the eight soil profiles is presented in Table 7. In the southern region, the profiles in Cafine were both categorized as Thionic Gleysols, exhibiting pronounced gleyic properties, with vertic characteristics evident in the upper horizons. These soils frequently undergo severe acidification due to the presence of hydroxysulfates, indicating their thionic nature. Additionally, CA TM exhibits significant salic and sodic properties in the deeper layers. In the northern region, the profiles in Elalab were classified as Eutric Gleysols, characterized by substantial sodic influence throughout all horizons, with arenic properties prevalent in the subsoil horizons of EL AM. Similarly, both profiles in Enchugal were classified as Eutric Thionic Gleysols, displaying notable salic (EN TM) and sodic (both) influences, while EN AM exhibited vertic properties consistently throughout the profile. Likewise, the Malafu MA TM profile was identified as Eutric Thionic Gleysol, featuring high salic and sodic accumulation in the deep layers. Notably, the MA AM profile stands out for its pronounced vertic properties across the profile, leading to its classification as a Sodic Vertisol, with the deepest layers exhibiting gleyic redoximorphic features.

3.4. Upland nurseries topsoil physical and chemical characterization

The soil physical properties for the upland nursery exhibited highly sandy textures (falling within the sandy and sandy loamy classes),

Table 6
Chemical parameters of the studied profiles.

Profile	Horizon	Al	Fe	TC	TN	EC $_{(1:2.5)}$	pH	Exch. acidity	Exchangeable cations and cations in solution				CEC	Av. P
									Ca	Mg	K	Na		
		%				dS m^{-1}	H_2O	cmol(+) kg^{-1}						mg kg^{-1}
	Ap	0.09	1.03	1.37	0.17	2.4	4.0	1.6	2.4	9.7	1.4	5.0	26.6	16
CA TM	AB	0.11	0.93	1.08	0.15	3.9	3.4	2.9	2.3	9.5	1.8	7.1	28.6	12
	Bg1	0.10	0.18	1.53	0.16	16.1	3.3	2.8	2.4	10.1	1.7	24.5*	25.7	23
	Bgj	0.16	0.12	1.51	0.17	26.1	3.0	7.4	3.0	13.6	1.0	39.2*	24.7	29
	Bg2	0.10	0.47	2.53	0.19	57.7	3.0	6.0	7.1	31.2	3.3	104.6*	25.2	31
	Ap	0.09	0.98	1.04	0.12	2.2	4.1	1.2	1.9	6.7	0.9	4.2	20.9	13
CA AM	AB	0.11	0.63	0.58	0.11	1.7	3.8	2.8	2.5	7.5	1.4	4.9	25.4	11
	Bi	0.10	0.48	0.70	0.11	3.1	3.5	3.9	2.3	6.4	0.9	6.0	23.5	20
	Bgj1	0.08	0.27	0.91	0.13	14.4	3.4	2.1	3.5	9.8	1.0	20.9*	23.2	14
	Bgj2	0.11	1.08	1.06	0.13	32.1	3.4	3.0	16.4	19.2	1.8	47.6*	24.8	62
	Bg	0.09	0.35	1.54	0.12	33.7	7.5	0.1	24.3	19.3	2.9	67.0*	19.4	61
EL TM	Ap	0.03	0.33	0.62	0.09	29.8	3.8	0.3	1.9	9.0	1.0	35.5*	6.5	6
	Bw	0.03	0.19	0.41	0.08	10.4	3.8	0.4	1.3	4.8	0.8	13.2*	10.6	4
	C	0.01	0.07	0.25	0.05	11.5	3.7	0.2	0.9	3.1	0.3	11.0*	3.1	4
	Cg	0.03	0.06	0.42	0.07	18.0	3.0	4.3	1.2	4.9	0.4	17.0*	5.4	21
EL AM	Ap	0.03	0.27	0.75	0.11	4.8	5.0	0.1	1.5	3.7	0.6	6.1	8.4	6
	Bw	0.04	0.22	0.47	0.09	4.7	6.1	0.1	1.7	4.5	0.9	8.5	12.9	5
	C1	0.01	0.02	0.09	0.03	3.4	5.0	0.1	0.5	0.9	0.1	2.5*	1.4	3
	C2	0.01	0.03	0.08	0.04	8.7	5.1	0.1	0.8	1.9	0.2	6.8*	1.2	3
	C3	0.01	0.08	0.15	0.04	11.0	4.7	0.1	1.0	2.4	0.3	7.4*	3.1	4
	Cg1	0.01	0.04	0.12	0.04	10.6	6.1	0.1	1.0	2.5	0.2	9.0*	1.3	4
	Cg2	0.02	0.04	0.14	0.03	11.1	3.5	2.2	1.0	2.9	0.1	9.4*	1.9	18
MA TM	Ap	0.1	0.71	1.19	0.14	3.5	4.8	0.4	1.9	9.8	1.3	9.1	23.5	11
	AB	0.09	0.48	0.73	0.11	6.4	4.7	0.3	2.0	10.9	1.5	15.9	23.5	12
	Bw	0.06	0.41	0.33	0.08	21.7	3.8	0.4	2.6	16.6	1.9	48.0*	25.0	9
	Bj	0.05	0.20	0.42	0.08	35.5	3.8	0.4	3.2	20.9	2.0	72.7*	23.4	15
	Bg1	0.06	0.12	0.46	0.08	43.6	3.4	1.6	3.4	22.5	2.1	86.9*	23.1	28
	Bg2	0.07	0.21	0.73	0.09	44.0	2.8	16.8	4.2	24.3	2.9	84.9*	24.7	20
MA AM	Ap	0.26	0.55	2.64	0.23	1.5	4.6	1.5	2.5	9.00	0.3	3.3	27.2	8
	Bi1	0.12	0.09	0.78	0.10	3.2	5.2	0.2	3.1	12.3	0.5	8.8	24.5	5
	Bi2	0.06	0.12	0.36	0.08	4.3	6.0	0.1	3.1	13.9	0.8	13.0	25.0	4
	Bi3	0.06	0.07	0.23	0.07	5.6	6.1	0.1	3.4	15.4	0.9	15.8	25.9	5
	Bg	0.06	0.12	0.18	0.07	5.9	4.9	0.3	3.5	15.9	1.0	15.5	26.5	7
EN TM	Ap	0.09	0.67	1.10	0.14	9.3	4.9	0.1	2.9	15.9	2.0	19.3	27.1	16
	Bw1	0.09	0.59	0.64	0.09	11.9	5.1	0.1	2.8	16.0	2.1	25.9*	29.5	44
	Bw2	0.08	0.25	0.32	0.09	21.3	5.4	0.1	3.2	19.7	2.4	50.9*	30.5	76
	Bj	0.07	0.20	0.32	0.09	30.6	6.2	0.1	3.8	23.6	2.7	71.6*	28.5	35
	Bg1	0.08	0,23	0.47	0.10	34.0	6.6	0.1	3.7	23.4	2.6	71.3*	27.3	68
	Bg2	0.08	0.24	1.04	0.13	47.0	2.8	4.5	4.4	33.3	2.9	90.6*	27.6	33
EN AM	Ap	0.11	0.53	0.97	0.13	4.5	5.1	0.2	2.8	11.9	1.5	9.7	25.9	7
	Bij1	0.07	0.18	0.69	0.10	7.1	4.4	0.4	2.7	9.9	1.5	15.4	23.9	9
	Bij2	0.04	0.10	0.61	0.08	8.3	4.1	0.4	2.6	9.9	1.3	19.4	21.7	9
	Bi	0.06	0.01	0.98	0.09	13.5	4.3	0.3	3.1	11.1	1.4	29.4*	23.9	40
	Bg	0.08	0.28	4.27	0.14	27.6	2.6	25.6	4.5	15.1	1.9	43.7*	29.4	21

Note: * indicate Na values that also comprise soluble salts; EC (Electrical Conductivity in extract soil: water 1:2.5), Exch. acidity (Exchangeable acidity), CEC (Cation Exchange Capacity), TC (Total Carbon), TN (Total Nitrogen), Av. P (available phosphorus).

except for Malafu 1 nursery, which is less sandy (classified as loam, Table 8). Having a small interparticle cohesion, moderate to high bulk densities are also recorded $1.42 < Db < 1.79$ g cm^{-3} for all of them except for Malafu 1 nursery with 1.28 g cm^{-3} coinciding with the highest organic matter and C accumulations.

In the nurseries' topsoil, there is a recurring pH fluctuation characterized by higher acidity accumulation during the dry season, followed by a subsequent normalization with the onset of the first rains. These soils exhibit shallow depth and a significant presence of gravel, contributing to minimal soil depth. Moreover, these soils are susceptible to consistent nutrient leaching and runoff due to their restricted depth and pronounced fluctuations between extended periods of drought and intense rainfalls. Carbon and nitrogen concentrations are notably low, particularly in the Uncur and Blafchur nurseries (Table 9), while cation exchange capacity (CEC) does not exceed 4 cmol (+)/kg, indicating very poor nutrient retention capacity. Comparatively, the Malafu nurseries exhibit relatively better topsoil conditions than others (Table 8 and 9).

3.5. *Soil suitability assessment –SSA*

According to the climatic and biophysical conditions delineated in Table 3, two profiles, MA TM and EN TM, are categorized as moderately suitable due to their limitations concerning flooding periods. These profiles experience annual flooding depths ranging from 20 to 40 cm, slightly exceeding the ideal range of 10–20 cm (Sys et al.,1993). This permits the cultivation of the most common rice varieties, as farmers typically employ tall varieties and engage in early plowing and sowing to mitigate prolonged flooding, which can hinder rice growth.

Elalab profiles (TM and AM) exhibit limitations in texture, characterized by highly sandy and sandy loamy topsoils that are unfavorable for robust root growth. Displaying six out of nine chemical properties falling into the N – *marginal not suitable* class, indicating acidity issues, poor TC and TN, and significant salinization and sodicity problems, evidenced by high EC and ESP values. The CEC falls within the S3 – *marginal suitability* class, indicating substantial leaching of bases. The EL AM profile exhibits less severe restrictive properties, except for acidity, which is not an issue in this profile, categorized as *group C* (Table 10).

For Enchugal, EN TM profile also falls to the *group B*, presenting

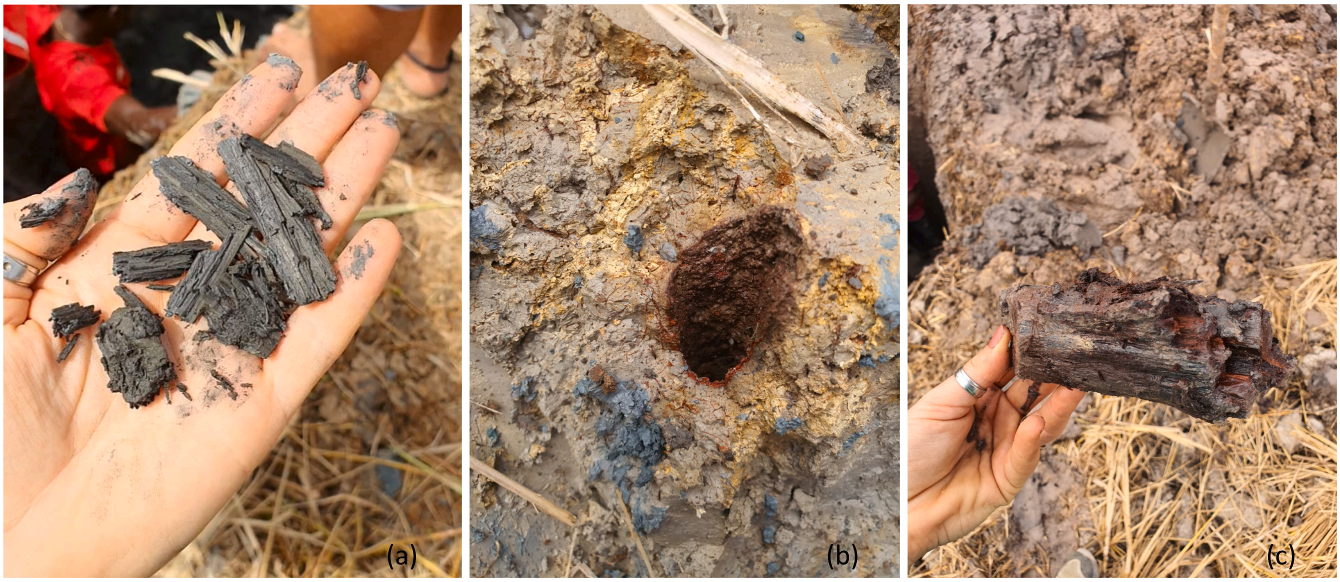

Fig. 5. (a) chunks found in Bg2 horizon of MA TM profile; (b) holes from root decomposition found in Bj and Bg1 horizons of EN TM profile; (c) chunks found in Bg horizon of EN AM profile. *Note:* chunks (a,c) and holes (b) indicate the deep-rooted ancient mangrove trees, confirming that these lands were once mangrove areas.

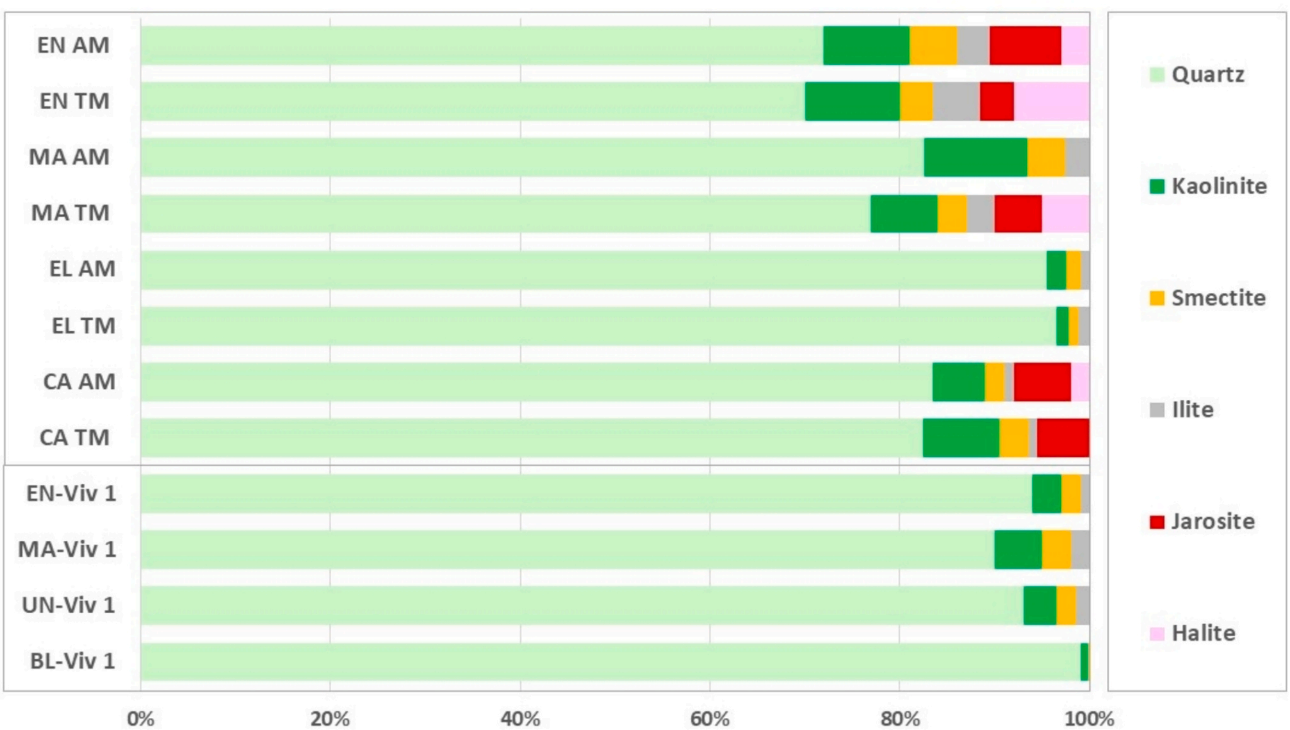

Fig. 6. Semi-quantitative average percentage of total mineral composition for each soil profile (average of all horizons), along with the average percentages of the topsoil nursery samples (2 for each point).

unsuitability (N) for EC, ESP, while pH and TC and N content fall within the S3 class. Meanwhile, the EN AM profile, even categorized in group B, has less restrictive properties, being sodicity the only N class, while salinity concentrations (EC) and TC and TN content are at marginally suitable levels (S3). Enhancing these soils through suitable amendments is feasible with effective management practices, albeit requiring significant time and effort from farmers especially for sodicity which is not easily corrected.

Both Malafu and Cafine, CF TM, CF AM, and MA AM are categorized in *group A*, having moderate acidity conditions and moderate limitations in TC and TN concentrations(S3). These soils are receptive to amendments, and the addition of organic materials can enhance soil properties and mitigate soil acidification. As well, MA TM has limitations primarily related to acidity and sodicidy accumulations, alongside low levels of organic decomposition, categorized under *group B*.

Regarding the nursery's topsoils, all of them are categorized under *group C* except for Malafu 1 which falls in *group B*. The primary limiting factors include topography (t) and physical properties (f), such as drainage, soil depth, and texture (see Table 11). These soils predominantly exhibit sandy and loamy sandy textures with coarse grain sizes,

Table 7
Soil profile classification according to IUSS Working Group WRB (2022).

Profile	WRB Classification
CA TM	**Thionic Gleysol** (clayic, salic, sodic, vertic)
CA AM	**Thionic Gleysol** (clayic, vertic)
EL TM	**Eutric Gleysol** (arenic, sodic)
EL AM	**Eutric Gleysol** (arenic, sodic)
MA TM	**Thionic Eutric Gleysol** (clayic, salic, sodic)
MA AM	**Sodic Vertisol** (clayic, gleic)
EN TM	**Thionic Eutric Gleysol** (clayic, salic, sodic)
EN AM	**Thionic Eutric Gleysol** (clayic, sodic, vertic)

Table 8
Mean values for physical properties for nursery topsoil.

Topsoil Sample	Sand (%)	Silt (%)	Clay (%)	Bulk Denisty (D_b) (g/cm^3)	Total Porosity (%)	Textural class
EN-Viv 1	60	10	30	1.44	55	Sandy loam
EN-Viv 2	79	8	13	1.79	68	Loamy sand
MA-Viv 1	31	22	47	1.56	59	Loam
MA-Viv 2	67	13	21	1.28	47	Sand clay loam
UN-Viv 1	72	12	16	1.54	66	Sand loam
BL-Viv 1	82	8	11	1.42	52	Loamy sand

resulting in high porosity and very low water retention capacities, leading to well-drained topsoils. Situated at higher elevations on slopes, these soils display significant gradients, which contribute to surface runoff and erosion, leading to the loss of weakly mineralized nutrients. This is reflected in their limited availability of nutrients such as N, C and P, as well as very low cation exchange capacities (CEC) and base saturation (BS) levels (classified as S3 and N1). Generally, they are shallow, often not exceeding 50 cm in depth, although this is not particularly restrictive for rice growth during the seedling early stages when the root system typically does not extend beyond 20 cm.

4. Discussion

4.1. Soil constraints in the upland rice nurseries

The characterization and suitability assessment of the examined profiles revealed that especially the physical properties exhibit overall favorable conditions for rice cultivation in these areas. On the contrary, the ferralitic upland nursery soils display significant limitations in physical properties, particularly in texture and soil depth. Nonetheless, constraints are less severe regarding slope gradient, drainage, and the abundance of coarse elements. Influenced by the parental material, typically coarse and nutrient-deficient soils are formed from acidic parent materials such as sandstones or quartzites (Balasubramanian et al., 2007). Tropic sandy soils are characterized by a large range of porosity and bulk density (Db,) with porosity ranging from 33 % for Db 1.7–1.8 g cm^{-3} to 47 % for Db 1.4 g cm^{-3} as reported for the sandy

Table 9
Mean values for main chemical parameters of nursery topsoil.

TopsoilSample	Horizon	Al	Fe	TC	TN	pH	EC	CEC	Ca	Mg	K	Na	BS	Av.P
		%				H_2O	(dS m^{-1})	cmol(+) kg^{-1}					%	mg L^{-1}
EN-Viv 1	Ap	0.138	0.176	1.64	0.18	6.51	0.26	0.25	0.11	0.08	0.04	0.02	100	64
EN-Viv 2	Ap	0.057	0.056	0.88	0.12	6.75	0.30	0.53	0.23	0.1	0.13	0.07	100	30
MA-Viv 1	Ap	0.187	0.406	2.04	0.16	5.97	0.14	3.92	1.81	1.1	0.09	0.09	79	7.7
MA-Viv 2	Ap	0.207	0.125	1.64	0.19	6.38	0.23	2.78	1.82	0.43	0.02	0.08	84	2.5
UN-Viv 1	Ap	0.119	0.090	0.88	0.12	6.33	0.21	1.43	0.32	0.0	0.06	0.08	31	5.1
BL-Viv 1	Ap	0.055	0.029	0.52	0.08	6.93	0.41	0.80	0.2	0.0	0.00	0.05	31	2.9

Note: EC (Electrical Conductivity), CEC (Cation Exchange Capacity), TC (Total Carbon), TN (Total Nitrogen), Av. P (available phosphorus).

Table 10
SSA classes rating for soil profiles.

Nr.	Soil Properties	CF TM	CF AM	MA TM	MA AM	EN TM	EN AM	EL TM	EL AM
1	Annual rainfall (mm)	S1	S1	S1	S1	S2	S2	S2	S2
2	Nr. Dry Months	S2	S2	S2	S2	S2	S2	S2	S2
3	Mean annual temp. (°C)	S1	S1	S1	S1	S1	S1	S1	S1
4	Relative humidity (%)	S1	S1	S1	S1	S1	S1	S1	S1
5	Slope gradient (%)	S1	S1	S1	S1	S1	S1	S1	S1
6	Drainage	S1	S1	S1	S1	S1	S2	S2	S2
7	Flooding	S1	S1	S3	S2	S3	S2	S1	S1
8	Soil depth (cm)	S1	S1	S1	S1	S1	S1	S1	S1
9	Texture	S1	S1	S1	S1	S1	S1	N	N
10	Gravel (%)	S1	S1	S1	S1	S1	S1	S1	S1
11	pH	S3	S3	S3	S3	S3	S2	N	S2
12	TC (%)	S3	S3	S3	S1	S3	S3	N	N
13	TN (%)	S3	S3	S3	S2	S3	S3	N	S3
14	Av. P (mg kg^{-1})	S1	S1	S1	S1	S1	S1	S2	S2
15	Exchange K (cmol kg^{-1})	S1	S1	S1	S2	S1	S1	S1	S1
16	CEC (cmol kg^{-1})	S1	S1	S1	S1	S1	S1	S3	S3
17	BS (%)	S2	S2	S1	S2	S1	S1	S1	S1
18	EC (dS m^{-1})	S2	S2	S2	S1	N	S3	N	S3
19	ESP (%)	S2	S2	N	S1	N	N	N	N
Total SSA	SSA Limited Groups	S3x3 = A	S3x3 = A	Nx1 S3 x4 = B	S3x1 = A	Nx4 S3x2 = B	Nx1 S3x3 = B	Nx6 S3x1=C	Nx3 S3x3 = B

Note: SSA classes: S1 = highly suitable/no limitation; S2 = Moderately Suitable or Slight Limitation; S3 = Marginally Suitable or Moderate Limitation; N= Permanently Not Suitable or Severe Limitation; A → (S3/N) ≤ 3, B → (S3/N) = 4 to 6, C → (S3/N) ≥ 7.

Table 11
SSA classes rating for nursery topsoils.

Nr.	Soil Properties	Enchugal 1	Enchugal 2	Malafu 1	Malafu 2	Uncur	Blafchur
1	Annual rainfall (mm)	S2	S2	S1	S1	S2	S2
2	Nr. Dry Months	S2	S2	S2	S2	S2	S2
3	Mean annual temp. (°C)	S1	S1	S1	S1	S1	S1
4	Relative humidity (%)	S1	S1	S1	S1	S1	S1
5	Slope gradient (%)	S3	S3	S2	S3	S2	S2
6	Drainage	S3	S3	S3	S3	S3	S3
7	Flooding	S1	S1	S1	S1	S1	S1
8	Soil depth (cm)	S3	S3	S3	S3	S3	S3
9	Texture	N	N	N	N	N	N
10	Gravel (%)	S2	S2	S2	S3	S3	S3
11	pH	S1	S1	S2	S1	S1	S1
12	TC (%)	S2	S3	S1	S2	S3	N
13	TN (%)	S3	S3	S3	S3	S3	N
14	Av. P (mg kg^{-1})	S1	S1	S1	S3	S2	S3
15	Exchange K (cmol kg^{-1})	N	S3	N	N	N	N
16	CEC (cmol kg^{-1})	N	N	N	N	N	N
17	BS (%)	S1	S1	S1	S1	S3	S3
18	EC (dS m^{-1})	S1	S1	S1	S1	S1	S1
19	ESP (%)	S1	S1	S1	S1	S1	S1
Total SSA	Total SSA classes	Nx3 S3x4=C	Nx2 S3x6=C	Nx3 S3x3 = B	Nx3 S3x6=C	Nx3 S3x6=C	Nx5 S3x5=C

Note: SSA classes: S1 = highly suitable/no limitation; S2 = Moderately Suitable or Slight Limitation; S3 = Marginally Suitable or Moderate Limitation; N= Permanently Not Suitable or Severe Limitation; A → (S3/N) ≤ 3, B → (S3/N) = 4 to 6, C → (S3/N) ≥ 7.

tropical topsoils by Bruand et al. (2005). The authors also contend that increases in bulk density invariably increase the penetration resistance with significant consequences for root development. Rice seedlings in the early stage have a weak root system, and the increased soil bulk density with wetting and drying cycles over the seedling stage importantly determines the balance of axial and radial pressures on the root tips, and hence the root elongation response (Bengough, 2012). In some cases, farmers use available animal manure to improve the soil in the nurseries. However, this practice remains quite limited, highlighting an opportunity to work with farmers on creating soft soil beds that facilitate rice growth and then uprooting for transplantation, which at the same time can increase soil fertility (Merkohasanaj et al**.**, forthcoming article).

4.2. Farmers battling climate change effects

Extreme weather events such as intense rainfall occurring within a short period, often coinciding with the transplantation phase, constitute a big risk to production. The flooding observed in these areas is attributed not only to intense rainfalls but also to the consistent soil saturation by tidal upwelling and surface runoffs is exacerbated by limited drainage capacity and insufficient traditional water management infrastructures. To mitigate these challenges, farmers implement strategies, such as selecting and utilizing rice varieties tolerant to high water levels' stress or performing early transplanting to preempt flooding. However, these efforts are not always successful, leading to inundation and subsequent production loss and, sometimes, to the abandonment of those areas when the main dike breaks and gullies are created in former plots. Farmers using collective initiatives often strive to implement last named techniques to enhance water management on their lands, but this is typically a challenging undertaking. Furthermore, both state and non-governmental interventions have been insufficient in the provision of water management infrastructures and dredging and cleaning of the country's main rivers, which are heavily laden with sediments (ONU-Habitat, 2019), thus limiting their water evacuation capacity. This involves not only the provision of PVC tubes to create a better water management infrastructure, but also cleaning and deepening existing channels, constructing new secondary channels, or expanding auxiliary storage embankments where possible.

Chemical characterization revealed distinct patterns among the profiles, particularly those heavily influenced by tidal effects (TM profiles), which exhibited significantly higher salinity and sodium issues compared to AM profiles, where concentrations only increased in the deeper layers. Since salinity and sodicity are frequently found in the same place (van Oort, 2018) high concentrations were particularly pronounced in the Elalab and Entchugal topsoils, possibly inducing severe limitations for rice production. In response to these challenges and under the constraints of highly uncertain climatic conditions (see Garbanzo et al. 2024a; Mendes and Fragoso, 2023), farmers developed soil stabilization techniques, albeit with only partial success in maintaining production levels. Factors such as topographic variations and drainage limitations, coupled with limited freshwater availability for salt and sodium leaching, often led to soil chemical imbalances, and eventually to the abandonment of many of these rice fields. This phenomenon aligns with observations by D'Amico et al. (2023), who noted that fields nearest to tidal creeks, with higher salt content, were typically the first to be abandoned. However, this trend does not apply to tidal mangrove (TM) rice fields in the southern region, which are typically the most productive and that have been farmed for decades. Instead, abandonment tends to occur in older rice fields located at higher gradients, closer to villages and away from tidal influences, due to factors such as fertility depletion, low organic matter content, acidification, and water drainage constraints (which farmers associate with a decrease in the number of months without rain). Similar trends have been observed in other villages of Oio region, such as Enchugal and Sugun. Farmers in this region traditionally allowed saltwater to enter the tidal marshes during the dry season — a technique they claim increases soil fertility while simultaneously controlling weed growth (van Gent and Ukkerman, 1989). However, this practice is becoming less common due to concerns about the availability of sufficient water to flush out the introduced salt.

4.3. Acid sulphate soils (ASS) challenges

The pH and acidity constraints can simultaneously happen in saline and/or sodic soils. Hydromorphic acid sulphate soils (ASS) suffer severe acidification even in the topsoil as pyrites at shallow depths may have resulted in subsurface materials being mixed with topsoils (Baggie et al., 2018, van Gent and Ukkerman, 1989). In these conditions, pH decreases drastically, and Al and Fe toxicity increases only when ASS are drained (Balasubramanian et al., 2007). Sluggish water, extremely accelerates the kinetic bio-chemical activity (cases where stagnant water in the fields reached temperatures above 40 degrees), accelerating reduction conditions that are commonly observed in mangrove soils (Sahrawat, 2004). Commonly, iron-reach upland soils generally do not exhibit iron toxicity since they are not subject to flooding. On the other hand, in the low flooded lands high parental iron and sulfur accumulations, in highly reduced conditions pared with poor drainage, mobilized and reduced from Fe^{3+} to Fe^{2+} which are toxic for the plants in high concentrations (Backer and Asch, 2005, Sahrawat, 2004).

The very high exchangeable acidity found in the deeper layers is related to the sulphide oxidation, producing jarosite ($KFe_3(SO_4)_2(OH)_6$) as a secondary mineral phase, evinced by yellow mottles formation, which is strong evidence of acid sulfate soil (Andretta et al., 2014; Zhu et al., 2008). Jarosite mottles after being oxidized, convert to orange and red goethite (FeO(OH)) and hematite mottles (Fe_2O_3) (Dent, 1986). As characterized in this study and described by Dent and Pones (1995), Acid Sulfate Soil (ASS) Gleysols typically exhibit highly waterlogged conditions at depth, characterized by a gray layer overlaid by a layer containing jarosite and goethite mottles. This layer is further overlain by a horizon with pronounced red hematite and goethite mottles, maintaining high acidity with a pH of around 4 and containing elevated levels of exchangeable aluminum. Finally, a dark-colored topsoil with slightly higher organic content caps the profile. Likewise, consistent patterns were observed in most of the profiles under investigation, notable for the presence of jarosite mottles extending below the Ap horizons, demonstrating that the high S and Fe concentrations can inhibit even in the rice root zone. Farmers identify the severe effects of acidity by the yellow–red coloration of the water and soil, which they refer to as '*conra*' (meaning toxicity in the Balanta language), as well as through significant production losses. To address these issues, they typically add large quantities of rice straw to the affected areas over several years (which according to them, absorbs toxicity) and allow animals to graze in these areas.

4.4. Soil nutritional imbalances and peculiarities

Highly acid conditions and iron (Fe^{2+}) concentrations in the first layer of soil solution can significantly impede the rice plant's absorption of vital nutrients, particularly phosphorus (P) and potassium (K), posing a serious threat to its growth and development (Olaleye et al., 2001). Nevertheless, soil suitability assessment (SSA) indicates no limitation in P and K levels within the topsoil, or even in deeper horizons exhibiting increased P availability. This phenomenon is likely attributed to ferric iron-bound phosphorus serving as a source of P following iron reduction and subsequent release of $H_2PO_4^-$, which acts as a minor yet significant P source for rice cultivation, partially satisfying plant requirements (Rakotoson et al., 2022; Wang et al., 2022). Nonetheless, it is demonstrated that nutritional disorders in rice plants due to potassium deficiency are exacerbated only when symptoms of iron toxicity become severe (Panhwar et al., 2016; Tadano and Yoshida, 1978), leading to yield reductions associated with poor soil nutritional status.

Profound gleyic horizons (those of Cafine and Enchugal extensively waterlogged) showed low bulk density with very high porosity and carbon increase in the deep horizons, possibly attributed to the high pore water oxygen; this causes clay expansion and increase in organic matter content due to plant material burrowed or mangrove residues deposited in the past (Adame et al., 2018; Andretta et al., 2014; Donato et al., 2011). Similar studies in the region reported higher OC (Organic Carbon) concentrations and consequently soil organic carbon storage in the deeper rice fields' layers (Andretta et al., 2016) and showed the strong relation between the OC, OM and bulk density (Adame et al., 2018). These lands were previously covered by mangrove forests whose soils are characterized by high OC content also in the deepest horizons, which are subjected to prolonged hydromorphic conditions, slowing down and preventing organic carbon decomposition and mineralization. As suggested by a large body of research, mangrove paddy soils facilitate and promote long-term SOC storage by occlusion within microaggregates and adsorption to the silt and clay outside microaggregates (Huang et al., 2014), or even resulting from larger stubble returns (Cui et al., 2014).

The low nitrogen levels found in almost all profiles may be attributed to the very low N mineralization, leaching and denitrification in anaerobic conditions, and the high and persistent extraction of nutrients due to plant demand (Yang et al., 2016; Kader et al., 2013; Ishii et al., 2011). As also explained by Hesse (1961) in the comparative study between *Rizophora* sp. and *Avicennia* sp. soils of Sierra Leone, slowly dried fibrous paddies of *Rhizophora* reached strong acidity conditions which inhibit N mineralization. Among other reasons, this could be one of the factors why farmers also claim to prefer lands previously occupied by *Avicennia*. However, this remains uncertain, as farmers in the northern part of the country assert that the decomposition of *Rhizophora* enhances soil fertility in the long term.

4.5. Overcoming soil constraints and build opportunities for future rice production

The physical properties of clay soils are often significantly influenced by the exchange of ions occurring within the clay matrix. Specifically, the plastic properties of clay soils are determined by the type of exchangeable cation, depending on whether Na^+ or Ca^{2+} is the exchangeable cation, as documented by Grim (1968). Furthermore, knowing better soil plasticity limits will help farmers define the optimal moment to start tillage (Garbanzo, et al., 2024b) or even the possibility of mechanization in specific areas of the paddies. Mechanization in recent years has been introduced in various areas of the country, to help farmers deal with labor constraints. However, mechanization has various limitations in these clay-rich soils and must be tried with care to avoid soil compaction. This can affect soil water storage and moisture and change plant diversity and promote further infestation (Singh et al., 2023), as was the case of an experiment conducted by a project in Cafine. Furthermore, the hydromorphy of the MSR fields makes it difficult for heavy machinery to operate properly, leading to frequent breakdowns and creating maintenance challenges for farmers. On the contrary, mechanization of plowing in the abandoned unfertile plots of the top of the catena, combined with the planting in alleys of native legume trees should be tried to reduce food insecurity.

The study highlights a critical gap in understanding and characterizing the region's soils and the extent of their coverage within the MSRP system. By employing transects across various regions, it provides an essential overview of the coastal MSRP system in Guinea-Bissau. The last comprehensive soil classification, conducted by Teixeira in 1962, estimated that hydromorphic soils covered 20 % of the country (approximately 650,000 ha). More recent work by Adefurin and Zwart (2013), using satellite imagery, identified Guinea-Bissau as having the highest percentage of rice cultivation in mangrove ecosystems among West African countries, with 3–5 % of the national area (approximately 102,100 ha) under cultivation. Most of this area falls within the MSRP system, underscoring the importance of soil characterization studies to support sustainable practices and informed land management. Importantly, the developed approach of this study was based on the "farmer-back-to-farmer" model of agricultural development suggested by Crane (2014), which ̈urge to the scientific knowledge system use farmers ́ knowledge and practices as both the starting point and endpoint of the value of innovation ̈, such approach is essential for addressing the challenges of agricultural productivity, environmental conservation, and resilience in these unique and sensitive ecosystems.

5. Conclusions

Coastal farmers of West Africa created a highly sophisticated production system in a rather challenging environment, for which local knowledge of soil broad characteristics and changes under aerobic conditions was mandatory. Their constant innovations were able to make MSR cultivation the most productive rice system without the use of chemical fertilizers, herbicides, and forced irrigation. However, the reduction in the number of months with rain, increased irregularity in the dates of the start and end of the rainy season, and more frequent and longer dry spells made farmers' knowledge, skills, and strategies poorly equipped to face climate change impacts in terms of soil fertility and toxicity. A limited amount of rainfall stored in the plots during the rice growth cycle is responsible for nutrient imbalance, acidity, salinity and sodicity problems, therefore critically reducing crop yields. The fragility and complexity of this agroecosystem, compounded by the absence of enough scientific knowledge about these soils and their dynamics of change after polderization, makes any external intervention aimed at increasing MSR production and productivity through improving soil fertility or mechanization prone to failure. It is important to emphasize that certain limitations, such as sodicity, acidity and the depletion of carbon and nitrogen, require further in-depth study. This will help develop solutions that can be effectively applied across the different study areas, complementing farmers' traditional practices.

This study makes an important contribution to the knowledge about soil characteristics and the spatial distribution of soil physicochemical properties within the MSRP system in GB, and West Africa in general. Additionally, the innovative approach of combining soil characterization and suitability assessment with farmer's local practices highlighted significant spatial variations across regions and agroecologies, demonstrating that even over very short distances, the soil's chemical properties can vary significantly, what makes it more difficult for farmers to innovate or adapt their practices. Furthermore, limitations identified in this characterization for suitability assessment will be further scrutinized concerning the productivity constraints associated with farmers' preferred rice varieties in a companion article (Merkohasanaj et al., 2025). Nonetheless, additional research is required to better understand how these variations affect farmers' rice yields, followed by the co-production of technological innovations with farmers aiming at increasing production and productivity through agroecological techniques. These can include: a) the introduction of compost, rotation with short cycle beans (a traditional technique now hampered by lack of appropriate seeds and unsupervised cattle roaming) and/or the planting of legume endogenous trees in alleys in the uplands where rice nurseries are made; b) the reintroduction of the traditional technique of allowing the entrance of brackish water to reduce soil acidity levels and increase fertility in TM plots, after the introduction of water management infrastructures by development projects (such the ones introduced by NGO Univers-Sel).

CRediT authorship contribution statement

Matilda Merkohasanaj: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriel Garbanzo:** Writing – review & editing, Visualization, Validation, Investigation, Data curation. **Nuno Cortez:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Francisco José Martín Peinado:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Anna Andreetta:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Cristina Cunha-Queda:** Writing – review & editing. **Marina Temudo:** Writing – review & editing, Resources, Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT services in order to correctly check and improve language readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Funding

This work was done with the financial assistance of the European Union, DeSIRA project 'Mangroves, mangrove rice and mangrove people: sustainably improving rice production, ecosystems and livelihoods' (Grant Contract FOOD/2019/412–700).

Data availability

Data will be provided upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The support from the Soil and Water laboratory in Bissau, the soil laboratory at the School of Agriculture (ISA) of the University of Lisbon, the laboratory of Soil and Agricultural Chemistry of the University of Granada (UGR) and a special gratitude to Antonio Delgado Huertas form the Stable Isotope Biogeochemistry Laboratory Instituto Andaluz de Ciencias de la Tierra (IACT). The authors extend especial gratitude to Merlin Leunda-Martiarena, Juvinal Silva Santos, Adinane Jalo, Paulina Na-Bitchom, Eduino Mendes da Costa, Adriano Barbosa and Alqueia Intchama for their unconditional support, meticulous sample collection and laboratory analyses, and hard field work in the study sites of Guinea-Bissau.

References

Adame, M.F., Zakaria, R.M., Fry, B., Chong, V.C., Then, Y.H.A., Brown, C.J., Lee, S.Y., 2018. Loss and recovery of carbon and nitrogen after mangrove clearing. Ocean Coast. Manag. 161, 117–126. https://doi.org/10.1016/j.ocecoaman.2018.04.019.

Adefurin, O., Zwart, S., 2013. A detailed map of rice production areas in mangrove ecosystems in West-Africa in 2013. Mapping of mangrove rice systems using Landsat 8 satellite imagery and secondary data. Africa Rice GIS Report – 2. Africa Rice Center, Cotonou, Benin.

Andreetta, A., Delgado, H.A., Lotti, M., Streng Cerise, S., 2016. Land use changes affecting soil organic carbon storage along a mangrove swamp rice chronosequence in the Cacheu and Oio regions (northern Guinea-Bissau). Agr. Ecosyst. Environ. 216, 314–321. https://doi.org/10.1016/j.agee.2015.10.017.

Andriesse, W., Fresco, L.O.A., 1991. Characterization of rice-growing environments in West Africa. Agr. Ecosyst. Environ. 33, 377–395. https://doi.org/10.1016/0167-8809(91)90059-7.

Backer, M., Asch, F., 2005. Iron toxicity in rice-conditions and management concepts. J. Plant Nutr. Soil Sci. 168, 558–573.

Baggie, I., Sumah, F., Zwart, S.J., Sawyerr, P., Bandabla, T., Kamara, S.C., 2018. Characterization of the mangrove swamp rice soils along the Great Scarcies River in Sierra Leone using principal component analysis. Catena 163, 54–62.

Balasubramanian, V., Sie, M., Hijmans, R.J., Otsuka, K., 2007. Increasing rice production in Sub-Saharan Africa: challenges and opportunities. Adv. Agron. 94, 55–133. https://doi.org/10.1016/S0065-2113(06)94002-4.

Beck, H.E., Zimmermann, N.E., Mc Vicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Koppen-Geiger climate classification maps at 1-Km resolution. Sci. Data 5, 180214.

Bengough, A.G., 2012. Root elongation is restricted by axial but not by radial pressures: so what happens in field soil? Plant and Soil 360, 15–18. https://doi.org/10.1007/s11104-012-1428-8.

Bertrand, F., 1991. Les relations sols/végétation dans les mangroves des pays des Rivières du Sud. État de la question et perspectives de débat. Dynamique et usages de la mangrove dans les pays des rivières du Sud, du Sénégal à la Sierra Leone, édité par Marie-Christine Cormier-Salem, IRD Éditions, ORSTOM Éditions. Doi: 10.4000/books.irdeditions.3702.

Bock, M.G., Pettapiece, W.W., Brierley, A.J., Bootsma, A., Schut, P., Neilsen, D., Smith, C.A.S., 2018. The land suitability rating system is a spatial planning tool to assess crop suitability in Canada. Front. Environ. Sci. 6, 77. https://doi.org/10.3389/fenvs.2018.00077.

Bouyoucos, G.J., 1936. Directions for making mechanical analysis of soils by the hydrometer method. Soil Sci. 4, 225–228.

Bruand, A., Hartmann, C., Lesturgez, G., 2005. Physical properties of tropical sandy soils: a large range of behaviours. Bangkok: FAO, p. 148-158. Symposium on Management of Tropical Sandy Soils for Sustainable Agriculture: Session 4. Physical Properties of Tropical Sandy Soils, 1.

Buol, S.W., Southard, R.J., Graham, R.C. and McDaniel, P.A., 2011. Soil Genesis and Classification. 6th Edition, John Wiley & Sons, Inc., West Sussex. Doi: 10.1002/9780470960622.

Crane, T.A., 2014. Bringing science and technology studies into agricultural anthropology: technology development as cultural encounter between farmers and researchers. Cult. Agric. Food Environ. 36 (1), 45–55.

Cui, J., Li, Zh., Liu, Z., Ge, B., Fang, Ch., Zhou, Ch., Tang, B., 2014. Physical and chemical stabilization of soil organic carbon along a 500-year cultived soil chronosequence originating from estuarine wetlands: Temporal patterns and land use effects. Agriculture, Ecosystems & Environment 96, 10-20, ISSN 0167-8809. Doi: 10.1016/j.agee.2014.06.013.

D'Amico, M.E., Barbieri, M., Khair, D.A.E., Comolli, R., 2023. Mangrove rice productivity and pedogenic trends in Guinea-Bissau. West Africa. J. Soils Sediments 24, 244–258.

Day, P.R., 1965. Particle fractionation and particle size analysis. In Black CA (ed.), Methods of soil analysis vol. 1. American Society of Agronomy, Madison, Wisconsin, p. 545–567.

Dent, D., 1986. Acid Sulphate Soils: A Baseline for Research and Development. International Institute for Land Reclamation and Improvement (ILRI Publ.39), Wageningen, Netherlands.

Dent, D.L., Pons, L.J., 1995. A world perspective on acid sulphate soils. Geodema 67, 263–276.

Donato, D., Kauffman, J., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geosci 4, 293–297. https://doi.org/10.1038/ngeo1123.

FAO, 1985. Guidelines: Land Evaluation for Irrigated Agriculture. FAO Soils Bulletin 55, FAO, Rome, 290.

FAO, 2007. The FAO guidelines for land evaluation. Available at: Land Use, Land Cover and Soil Sciences II, 1–9 https://www.eolss.net/Sample-Chapters/C12/E1-05-02-03.pdf.

FAO, 2024. Global Status of Salt-Affected Soils – Main report. Doi: 10.4060/cd3044en.

Forsythe, W.M., 1985. Fisica de suelos: manual de laboratorio. San Jose, Costa Rica. IICA. p.212.

Garbanzo, G., Cameira, M.d.R., Paredes, P., 2024a. The mangrove swamp rice production system of guinea-bissau: identification of the main constraints associated with soil salinity and rainfall variability. Agronomy 14, 468. Doi: 10.3390/agronomy14030468.

Garbanzo, G., Céspedes, J., Sandoval, J., Temudo, M., Paredes, P., 2024b. Moving toward the biophysical characterization of the mangrove swamp rice production system in Guinea-Bissau: exploring tools to improve soil and water-use efficiencies. Agronomy 14, 335. https://doi.org/10.3390/agronomy14020335.

Grim, R.E., 1968. Clay Mineralogy. International series in the earth and planetary sciences. McGraw-Hill, University of Minnesota.

Harris, S.A., 1973. Comments on the application of the holdridge system for classification of world life zones as applied to Costa Rica. Arct. Alp. Res. 5 (3), A187–A191. http://www.jstor.org/stable/1550169.

Hesse, P.R., 1961. Some differences between the soils of Rhizophora and Avicennia Mangrove Swamps in Sierra Leone. Plant and Soil 14 (4), 335–346. http://www.jstor.org/stable/42931916.

Horneck, D.A., Miller, R.O., 1998. Determination of total nitrogen in plant tissue. In: Kalra, Y.P. (Ed.), Handbook of Reference Methods for Plant Analysis. Soil and Plant Analysis Council Inc. and CRC Press, Boca Raton, FL, pp. 75–83.

Huang, S., Pan, X., Guo, J., Qian, Ch., Zhang, W., 2014. Differences in soil organic carbon stocks and fraction distributions between rice paddies and upland cropping systems in China. J. Soil. Sediment. 14, 89–98. https://doi.org/10.1007/s11368-013-0789-9.

Ishii, S., Ikeda, S., Minamisawa, K., Senoo, K., 2011. Nitrogen cycling in rice paddy environments: past achievements and future challenges. Microbes and Environents. 26 (4), 282–292. https://doi.org/10.1264/jsme2.ME11293.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps, 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Kader, M.A., Sleutel, S., Begum, S.A., Moslehuddin, A.Z.M., Deneve, S., 2013. Nitrogen mineralization in sub - tropical paddy soils in relation to soil mineralogy, management, pH, carbon, nitrogen and iron contents. European Journal of Soil Science 64 (1), 47-57. ISSN 1351-0754.

Klute, A., 1986. Water retention: Laboratory methods. p. 635–662. In A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods, second ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Linares, O.F., 1981. From tidal swamp to inland valley: on the social organization of wet rice cultivation among the Diola of Senegal. Africa 1981 (51), 557–595. https://doi.org/10.2307/1158828.

Marius, C., Lucas, J., 1982. Evolution geochimique et exemple d́aménagement des mangroves au senegal casamance. Oceanol. Acta 1, 10.

Martin, J.D., 2004. Using XPowder: A software package for Powder X-Ray diffraction analysis. www.xpowder.com, D.L. G 1001/04.

Marzouk, S.H., Tindwa, H.J., Massawe, B.H.J., Amuri, N.A., Semoka, J.M., 2023. Pedological characterization and soil fertility assessment of the selected rice irrigation schemes Tanzania. Front. Soil Sci. 3, 1171849. https://doi.org/10.3389/fsoil.2023.1171849.

Marzouk, Y., 1991. Histoire Des Conceptions Hydrauques Etatiques et Paysannes En Basse Cassamance, Senegal, 1960–1990. In Savoirs Paysans et Développement; Dupré, G., Ed.; Karthala-Orstom: Paris, France, Volume 1, pp. 61–97, ISBN 9786021018187.

Massawe, I.H., Msanya, B.M., Rwehumbiza, F.B., 2017. Pedological characterization and fertility evaluation of paddy soils of Mvumi Village, Kilosa District, Tanzania. Int. J. Curr. Res. Biosci. Plant Biol. 4 (4), 49–60.

Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15, 1409–1416.

Mendes, O., Fragoso, M., 2023. Assessment of the Record-Breaking 2020. Rainfall in Guinea-Bissau and Impacts of Associated Floods. Geosciences 13, 25. Doi: 10.3390/geosciences13020025.

Mota, T., 1954. Guiné Portuguesa; Agência Geral do Ultramar: Lisboa, Portugal, Volume 1.

Merkohasanaj, M., Cortez, N., Cunha-Queda, C., Andreetta, A., Cossa, V., Martin-Peinado, F.J., Temudo, M.P., Goulao, L.F., 2025. Linking soil fertility and production constraints with local knowledge and practices for two different mangrove swamp rice agroecologies, Guinea-Bissau West Africa. Agronomy 15, 342. https://doi.org/10.3390/agronomy15020342.

Olaleye, A.O., Tabi, A.O., Ogunkunle, A.O., Singh, B.N., Sahrawat, K.L., 2001. Effect of toxic iron concentrations on the growth of lowland rice. J. Plant Nutr. 24, 441–457.

ONU-Habitat, 2019. Plano de Desenvolvimiento Sustentável 2030. Programa das Nações Unidas para os Assentamentos Humanos (ONU-Habitat) 2019 e Camara Municipal Bissau.

Oosterbaan, R.J., 1982. Natural and social constraints to polder development in Guiné-Bissau. Polders of the World, Papers International Symposium Volume 1, The Netherlands.

Panhwar, A.Q., Naher, A.U., Shamshuddin, J., Radziah, O., Hakeem, R.K., 2016. Management of Acid Sulfate Soils for Sustainable Rice Cultivation in Malaysia. In: In Soil Science: Agricultural and Environmental Prospectives, pp. 91–104. https://doi.org/10.1007/978-3-319-34451-5_4.

Pravin, R.C., Dodha, V.A., Vidya, D.A., Manab, C., Saroj, M., 2013. Soil bulk density as related to soil texture, organic matter content and available total nutrients of coimbatore soil; Int. J. Sci. Res. Publ. 3(2) (ISSN: 2250-3153). http://www.ijsrp.org/research-paper-0213.php?rp=P14721.

Rakotoson, T., Tsujimoto, Y., Nishigaki, T., 2022. Phosphorus management strategies to increase lowland rice yields in sub-Saharan Africa: a review. Field Crop Res 275, 108370.

Richards, L.A., Fireman, M., 1943. Pressure plate apparatus for measuring moisture sorption and transmission by soils. Soil Sci. 56, 395–404.

Sahrawat, K.L., 2004. Iron toxicity in wetland rice and the role of other nutrients. Journal of Plant Nutrient. 27 (8), 1471–1504.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Soil Survey Staff, 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Singh, P.K., Kumar, A., Naresh, R.K., Singh, V.K., Tiwari, H., Bhatt, R., Tomar, S.S., Chandra, M.S., Mahajan, N.C., Kumar, L., Kataria, S.K., 2023. Mechanized paddy transplanting impacts on the productivity and sustainability of the rice cultivation system in North West IGP: a review. Agricultural Mechanization Asia 54 (6). ISSN: 00845841.

Soil Survey Staff, 2014. Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 5.0. R. Burt and Soil Survey Staff (Ed.). U.S. Department of Agriculture, Natural Resources Conservation Service. https://www.nrcs.usda.gov/sites/default/files/2023-01/SSIR42.pdf.

Syers, J.K., Rimmer, D.L., 1994. Soil Science and Sustainable Land Management in the Tropics.

Sylla, M., 1994. Soil Salinity and Acidity: Spatial Variability and Effects on Rice Production in West Africa's Mangrove Zone. Wageningen University and Research, Wageningen, The Netherlands.

Sylla, M., Stein, A., van Breemen, N., Fresco, L., 1995. Spatial variability of soil salinity at the different scale in the mangrove rice agro-ecosystems in west Africa. Agr1cu1ture. Ecosystems and Environment 54, 1–15. https://doi.org/10.1016/0167-8809(95)00594-I.

Sys, C., Van Ranst, E., Debaveye, J., 1991. Land evaluation, part I: Crop requirements. In: Agricultural Publications-No 7, General Administration for Development Cooperation Brussels. ISRIC Library, Belgium, p. 280.

Sys, C., Van Ranst, E., Debaveye, J., 1993. Land evaluation, part III: principles in land evaluation and crop production calculations. In: Agricultural Publications-No 7, General Administration for Development Cooperation Brussels. ISRIC Library, Belgium, p. 280.

Tadano, T., Yoshida, S., 1978. Chemical Changes in Submerged Soils and Their Effect on Rice Growth. In: Soils and Rice. International Rice Research Institute, Los Baños, pp. 399–421.

Teixeira, D.S., 1962. Os Solos Da Guiné Portuguesa. Carta General Caracteristicas, Formação e Utilização, 1st ed.; Junta de Investig ac.es do Ultramar: Lisboa, Portugal.

Temudo, M.P., 2011. Planting knowledge, harvesting agro-biodiversity: a case study of southern guinea-bissau rice farming. Hum. Ecol. 39, 309–321.

Temudo, M.P., Figueira, R., Abrantes, M., 2015. Landscapes of bio-cultural diversity: shifting cultivation in Guinea-Bissau West Africa. Agroforest Syst. 89, 175–191. https://doi.org/10.1007/s10457-014-9752-z.

Temudo, M.P., Santos, P., 2017. Shifting environments in eastern guinea-bissau, West Africa: the length of fallows in question. NJAS Wageningen J. Life Sci., 80, 57–64. https://doi.org/10.1016/j.njas.2016.12.001.

van Gent, P., Ukkerman, R., 1989. The Balanta rice farming system in Guinea-Bissau. 1250 mm, 103–122. In D. L dent and M.E.F. van Mensvoort (eds). Selected paper of Ho Chi Minh City symposium on acid sulfate soils. ILRI Pub.53. International Institute for Land Reclamation and Improvement, Wageningen, the Netherlands.

van Oort, P.A.J., 2018. Mapping Abiotic stresses for rice in africa: drought, cold, iron toxicity salinity and sodicity. Field Crop. Res. 219, 55–75. https://doi.org/10.1016/j.fcr.2018.01.016.

Wang, C., Thielemann, L., Michaela, A.D., Guggenberger, G., Kuzyakov, Y., Banfield, C. C., Ge, T., Guenther, S., Bork, P., Horn, A.M., Dorodnikov, M., 2022. Microbial iron reduction compensates for phosphorus limitation in paddy soils. Sci. Total Environ. 837, 155810.
Yang, Y., Zhang, J., Cai, Z., 2016. Nitrification activities and N mineralization in paddy soils are insensitive to oxygen concentration. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 66 (3), 272–281. https://doi.org/10.1080/09064710.2015.1093653.
Zhu, L., Lin, C., Wu, Y., Lu, W., Liu, Y., Ma, Y., Chen, A., 2008. Jarosite-related chemical processes and water ecotoxicity in simplified anaerobic microcosm wetlands. Environ. Geol. 53, 1491–1502. https://doi.org/10.1007/s00254-007-0758-y.